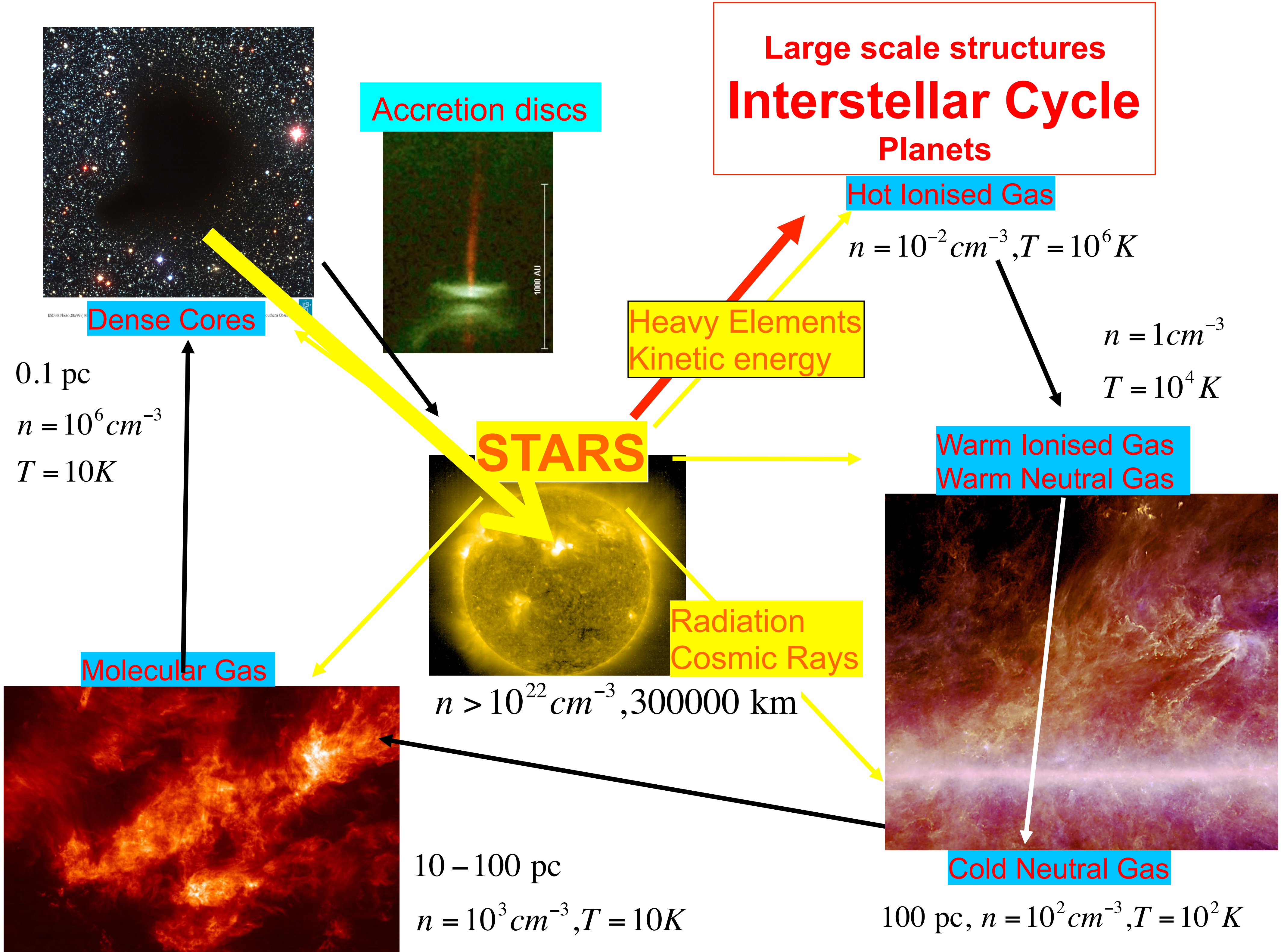
Collapse calculations with RAMSES:

Magnetic braking and its effects during protostellar collapse

When Magnetic Field leads to Catastrophe and Crisis

Patrick Hennebelle

Benoit Commerçon, Marc Joos, Jacques Masson, Andréa Ciardi
Sébastien Fromang, Romain Teyssier, Philippe André, Gilles Chabrier


Large scale structures
Interstellar Cycle
Planets
Hot Ionised Gas
$n = 10^{-2} cm^{-3}, T = 10^{6} K$
Accretion discs
1000 AU
Dense Cores
0.1 pc
$n = 10^{6} cm^{-3}$
$T = 10 K$
Heavy Elements
Kinetic energy
$n = 1 cm^{-3}$
$T = 10^{4} K$
STARS
Warm Ionised Gas
Warm Neutral Gas
Radiation
Cosmic Rays
Molecular Gas
$n > 10^{22} cm^{-3}$, 300000 km
10 – 100 pc
$n = 10^{3} cm^{-3}, T = 10 K$
Cold Neutral Gas
100 pc, $n = 10^{2} cm^{-3}, T = 10^{2} K$

Formation of the protostar: the second collapse

(Larson 69, Tohline 82, Masunaga & Inutsuka 02)

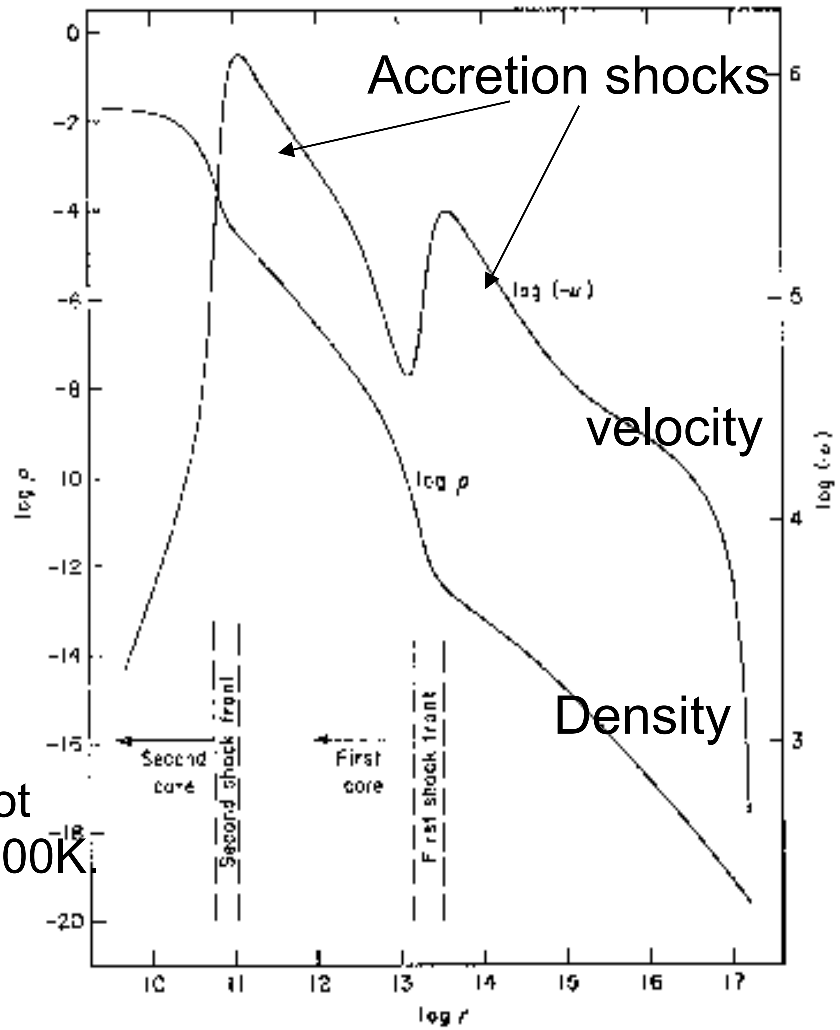
-$\rho < 10^{-13}$ g cm^{-3} :
nearly isothermal

- 10^{-13} g cm$^{-3} < \rho < 10^{-8}$ g cm^{-3} :
adiabatic phase (first Larson core)
The core is in hydrostatic equilibrium
(Effective γ = 5/3 – 5/4). Its mass grows by accretion.

- 10^{-8} g cm$^{-3} < \rho < 10^{-3}$ g cm^{-3} :
dissociation of the molecular hydrogen. The gravitational energy is used to dissociate H_2 (Saumon et al. 95) and not to heat the gas. Temperature stays nearly constant to 2000K.
The thermal support (Effective γ = 1.1) is not strong enough and the collapse restarts.

- $\rho > 10^{-3}$ g cm^{-3}: all hydrogene molecules have been dissociated
=>the gas becomes adiabatic,
=>Formation of the protostar

Larson 69



1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

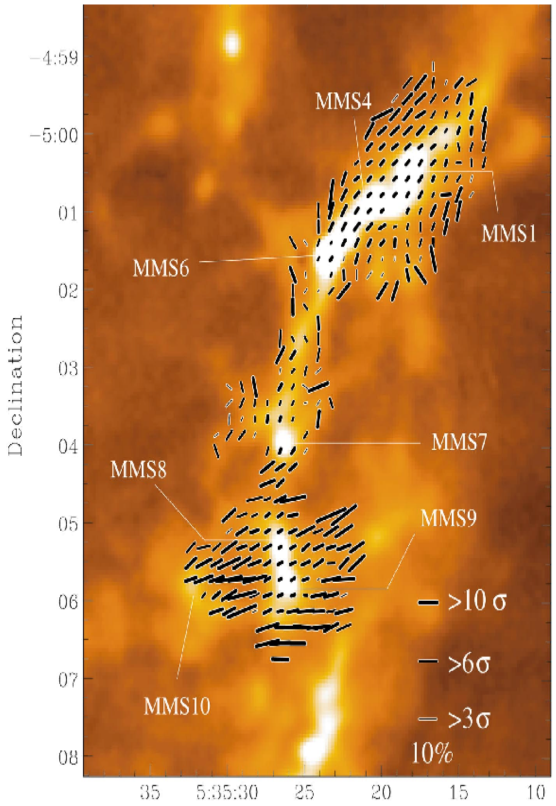
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

Intensity and structure of the magnetic field

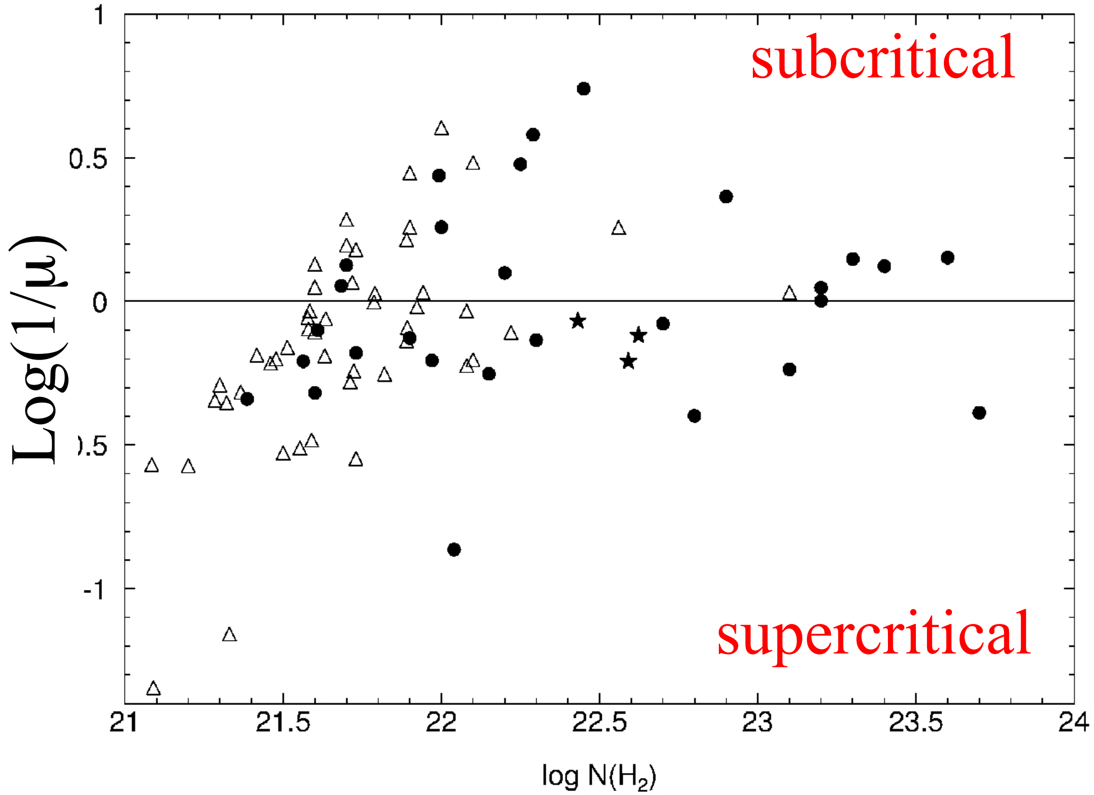
Zeeman effect in the OH molecule-polarisation (through dust grains alignment)

Polarisation map for Orion.
The polarisation is well organised
aligned (top) or perpendicular (bottom)
Helical structure has been proposed



Matthews et al. 2001

A sample of "corrected" Flux to mass over critical Flux to mass ratio

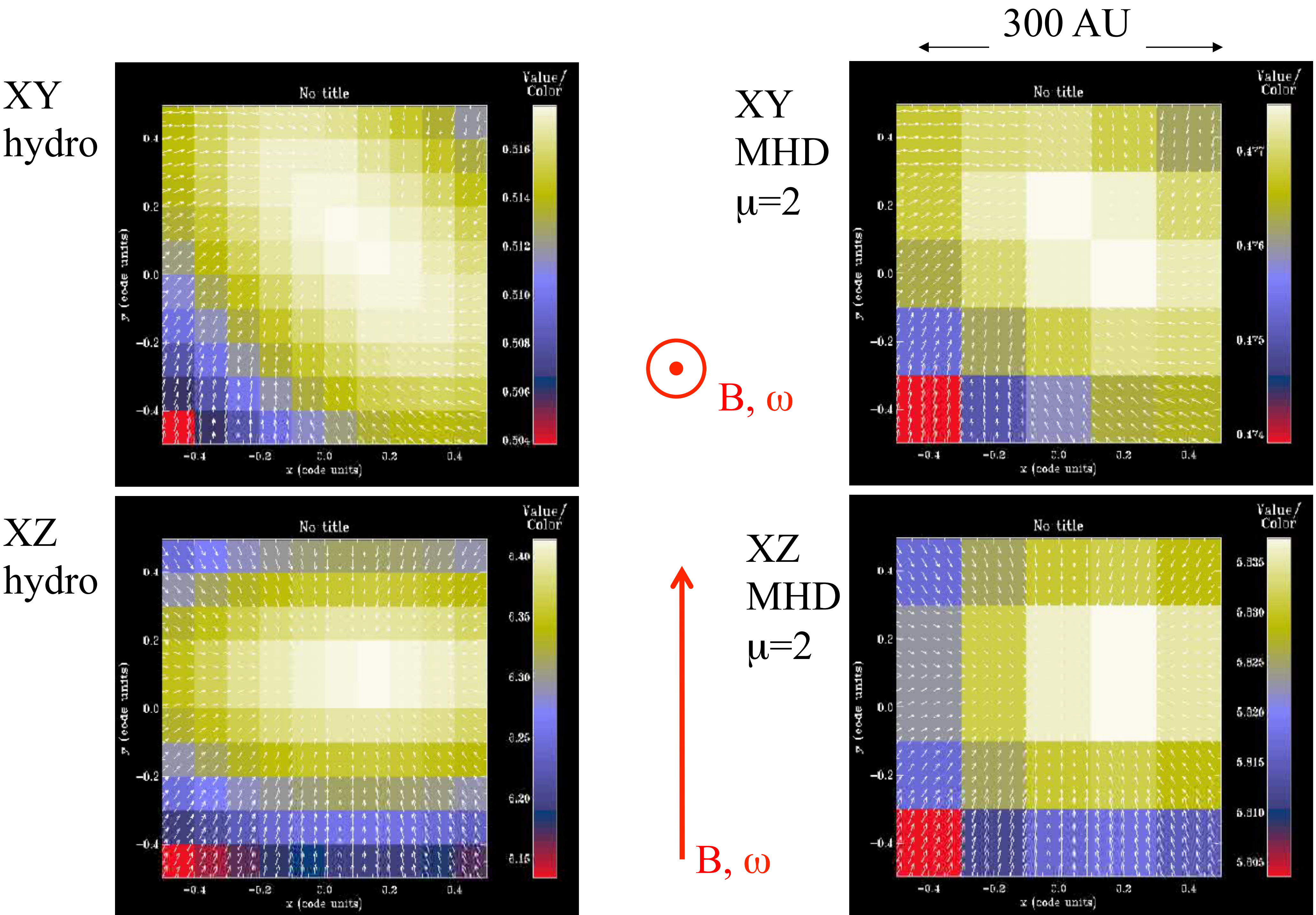


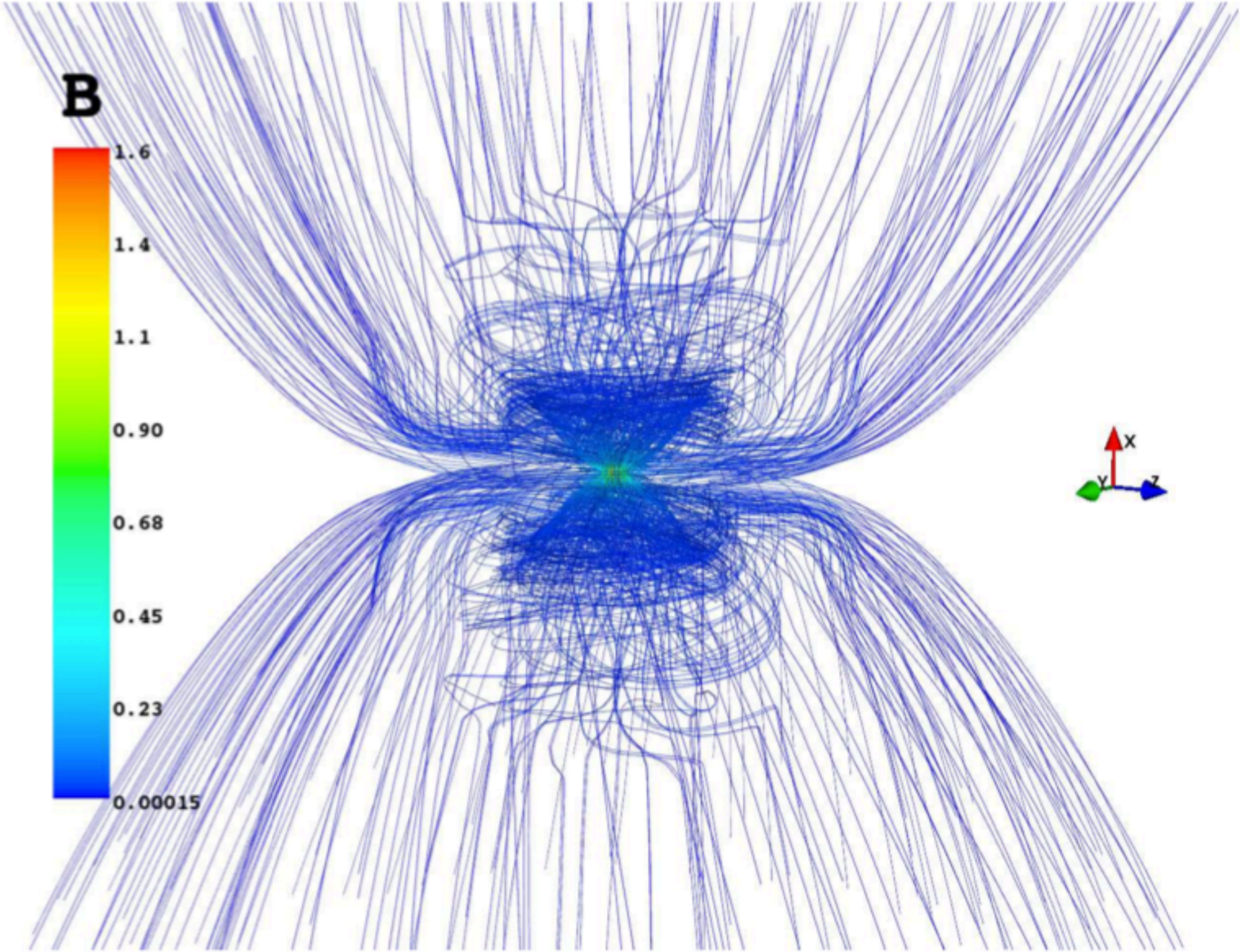
Crutcher 2004

Some cores seem to be critical. Magnetic field appears to be significant.

Zoom into the central part of a collapse calculation (1 solar mass slowly rotating core)

(Allen et al. 03, Machida et al. 05, Banerjee & Pudritz 06, Price & Bate 07, Hennebelle & Fromang 08)

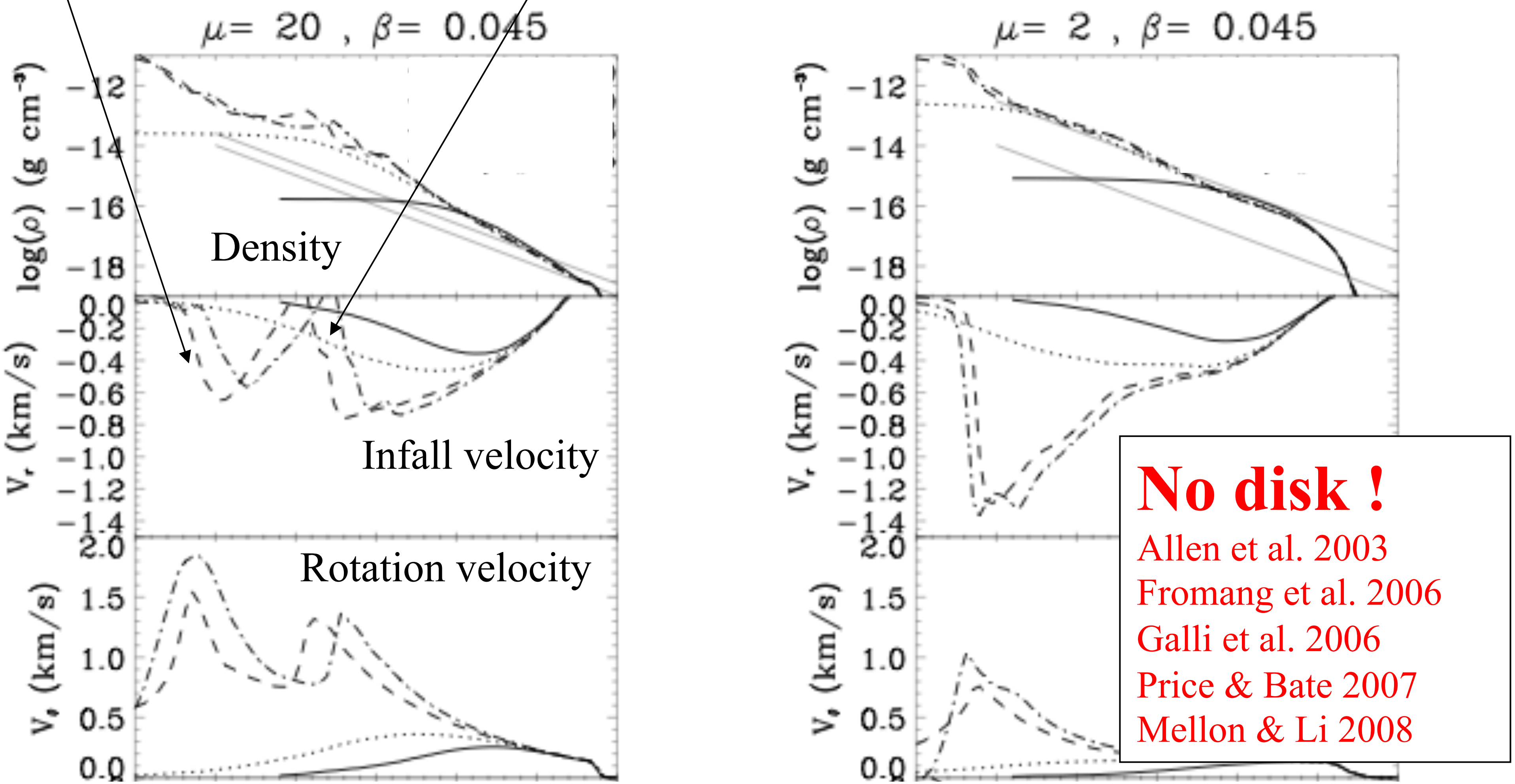



B
1.6
1.4
1.1
0.90
0.68
0.45
0.23
0.00015
X
Y
Z

Density, rotation and infall velocity profiles

Thermally supported core

Centrifugally supported disk



No disk !

Allen et al. 2003

Fromang et al. 2006

Galli et al. 2006

Price & Bate 2007

Mellon & Li 2008

Hennebelle & Fromang 2008

Can we understand this result by simple considerations ?

$$\left.\begin{aligned}\frac{\rho V_\theta}{\tau_{br}} &\propto B_z \frac{B_\theta}{4\pi h}\\ \frac{B_\theta}{\tau_{br}} &\propto B_z \frac{V_\theta}{h}\end{aligned}\right\} \Rightarrow \tau_{br} \approx \frac{\sqrt{4\pi h^2 \rho}}{B_z}$$

$$\tau_{rot} \approx \frac{2\pi\, r_d}{V_\theta},$$

$$\frac{\tau_{br}}{\tau_{rot}} \approx \frac{V_\theta \sqrt{4\pi h^2 \rho}}{2\pi\, r_d B_z}$$

$$V_\theta \approx \left(\frac{GM_d}{r_d}\right)^{1/2}, M_d \approx \pi r_d^{\;2} z\rho \Rightarrow V_\theta \approx \left(G\pi\rho r_d z\right)^{1/2}$$

$$\Rightarrow \frac{\tau_{br}}{\tau_{rot}} \approx \left(\frac{z}{r_d}\right)^{1/2} \frac{G^{1/2}\rho}{B_z} \approx \left(\frac{z}{r_d}\right)^{1/2} \frac{\mu_{eff}}{(2\pi)^{1/2}}$$

z/r_d is easily < 10 while $\mu_{eff} < \mu$ (as only a fraction of the column density has contracted)

Thus a value of μ~5-10 seems entirely reasonable.

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

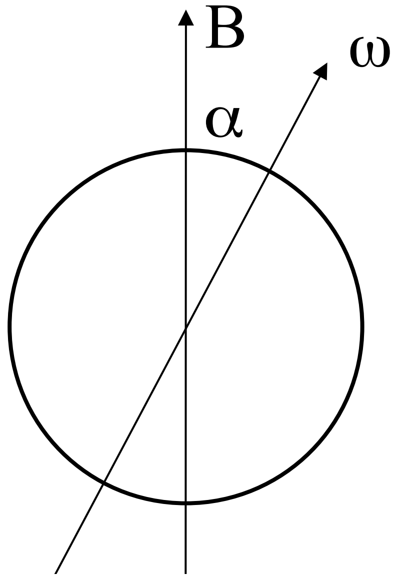
2.2) How to solve it ?

2.3) Influence of B on high mass cores

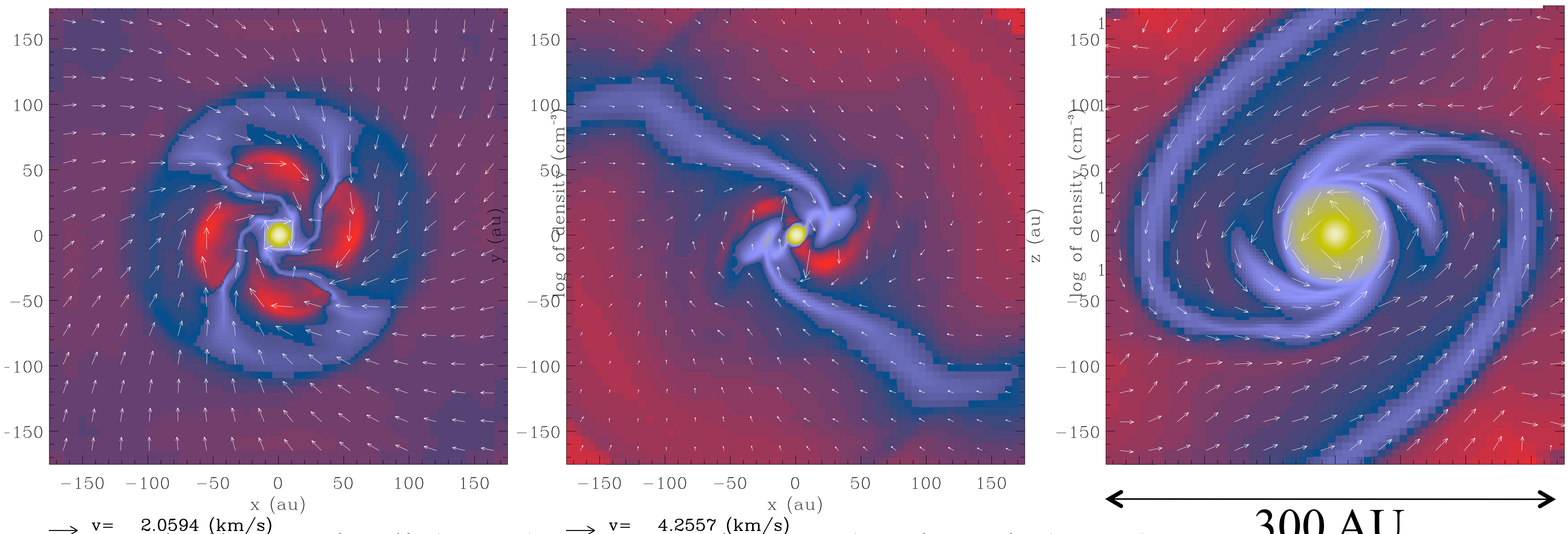
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

Can different magnetic configurations modify magnetic braking ?



μ=5,α=0° μ=5,α=20° μ=5,α=90°

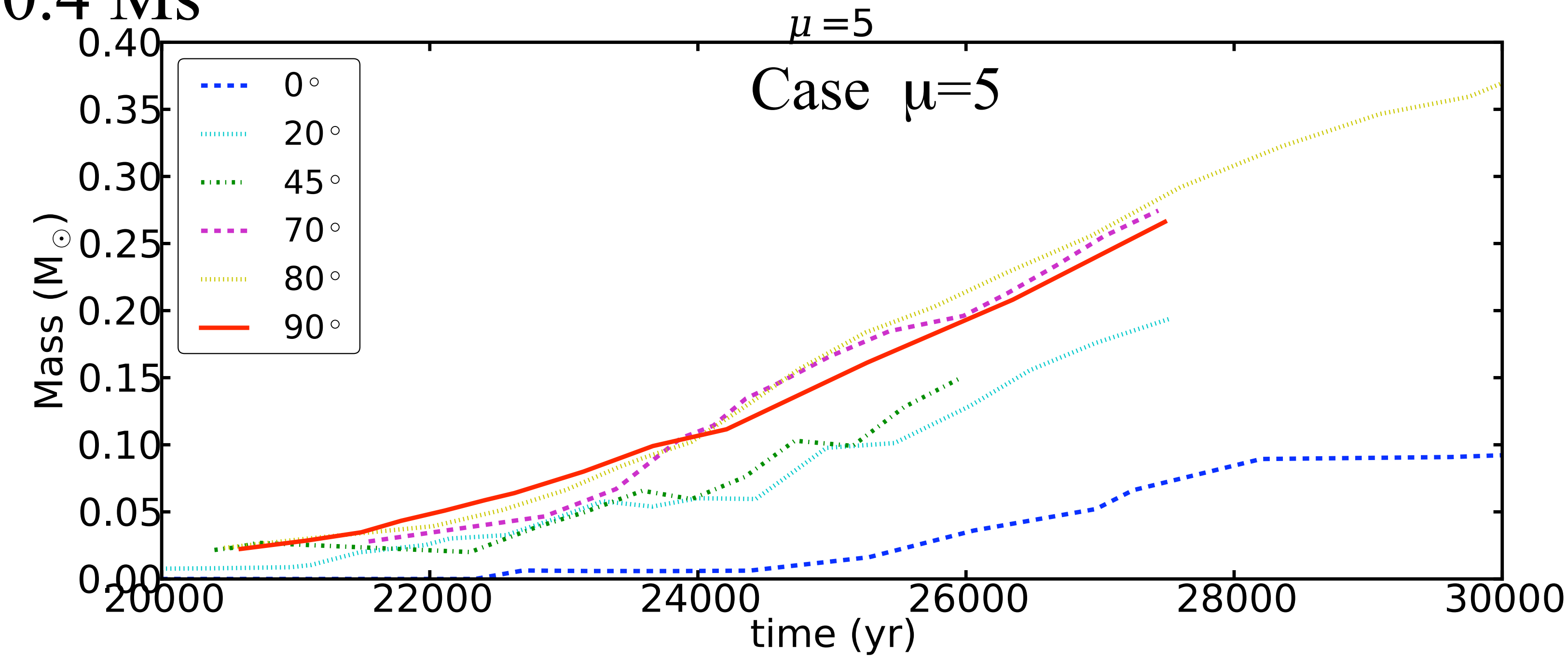


Hennebelle & Ciardi (2009), Joos et al. (2012), Li et al. (2013)

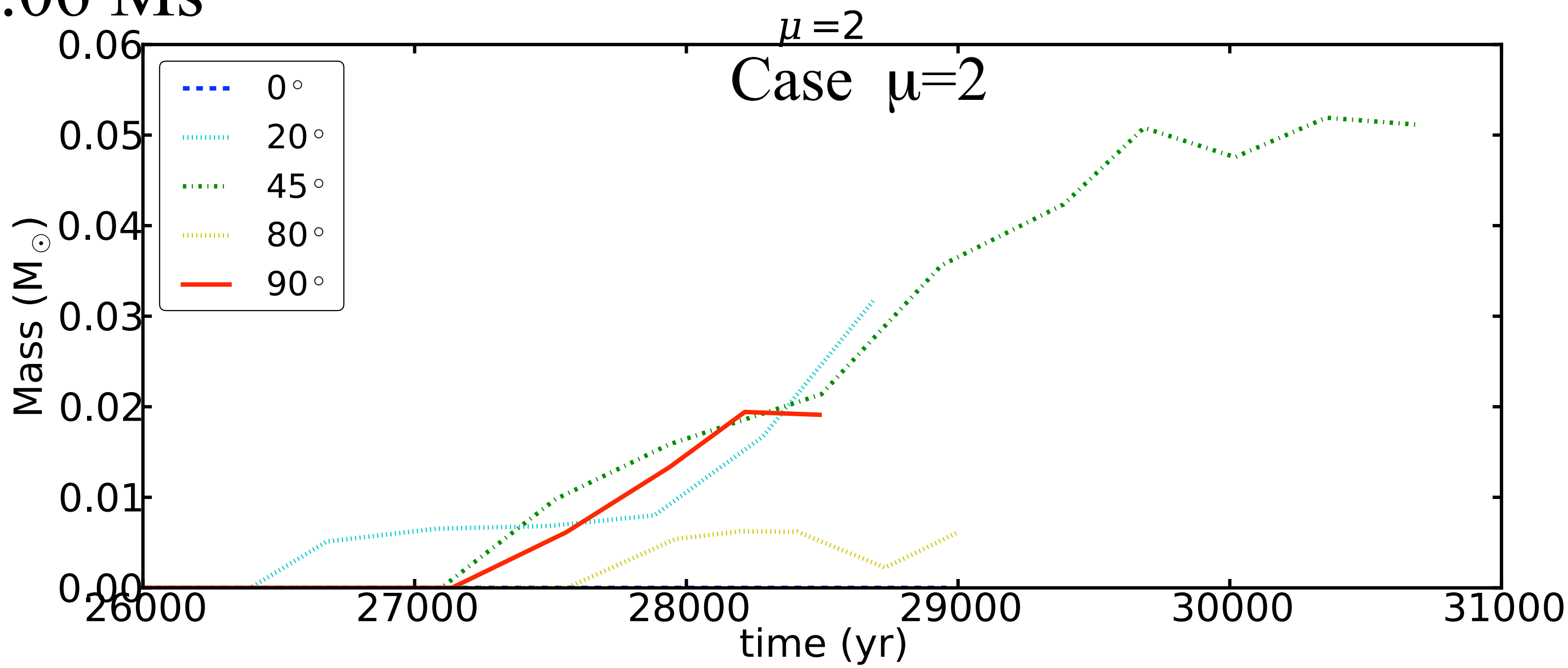
Joos et al. 2012

Disk mass vs time

0.4 Ms

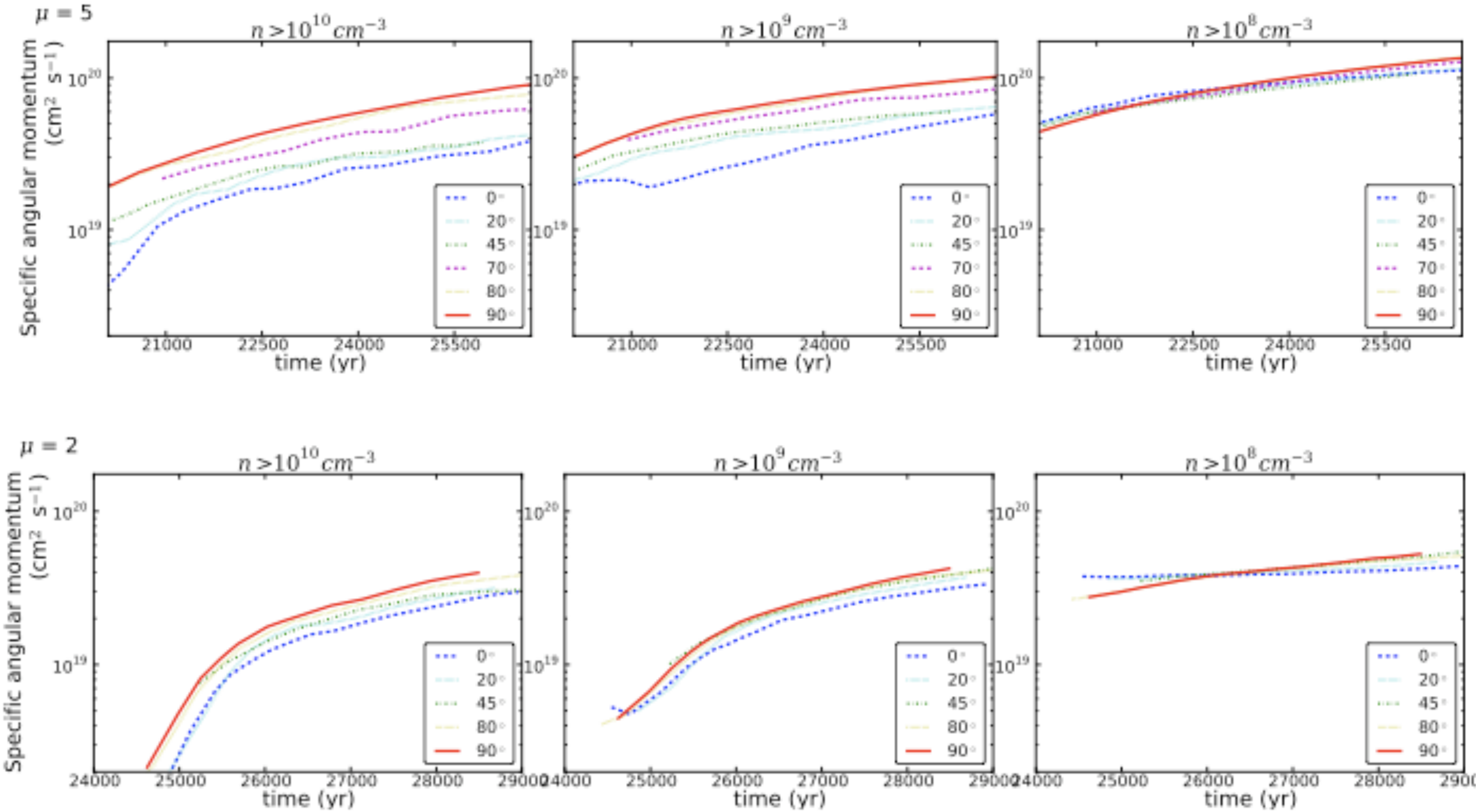


0.06 Ms



Joos et al. 2012

Specific angular momentum above various density thresholds

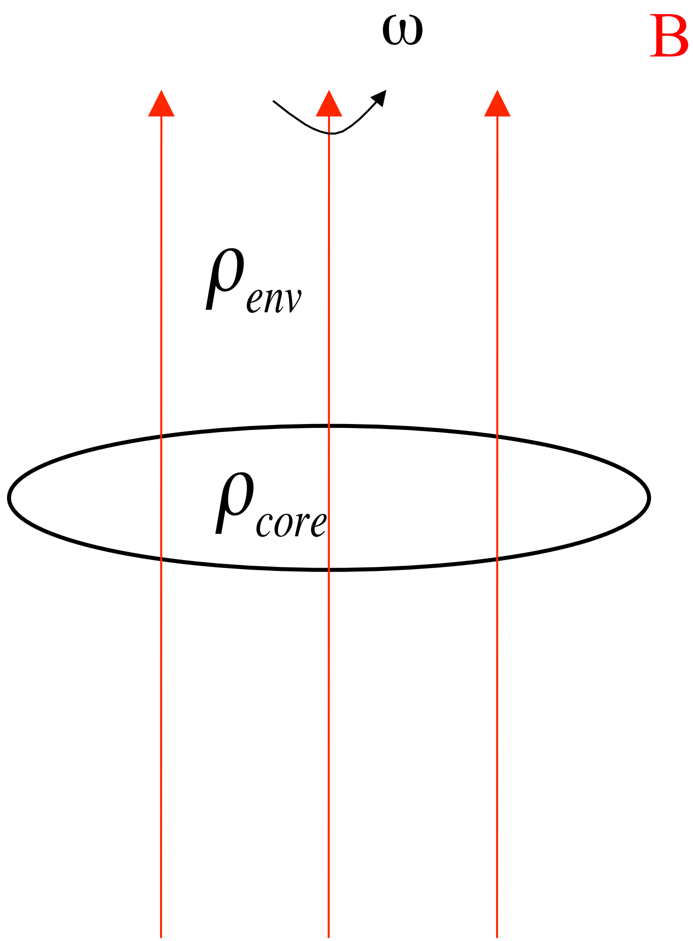


Magnetic braking

(Gillis et al. 74,79, Mouschovias & Paleologou 79,80, Basu & Mouschovias 95, Shu et al. 87)

rotation generates torsional Alfvén waves which carry angular momentum outwards

<u>Typical time:</u> AW propagate far enough so that the external medium receives angular momentum comparable to the cloud initial angular momentum



Magnetic field parallel to the rotation axis:

$$\rho_{core} Z_{core} \approx \rho_{env} \tau_{para} V_a$$

$$\Rightarrow \tau_{para} \approx (\rho_{core} / \rho_{env}) \times (Z_{core} / V_a)$$

$$\approx \frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}}$$

since $M = 2\pi Z_{core} R^2 \rho_{core}$ and $\phi = \pi R^2 B$

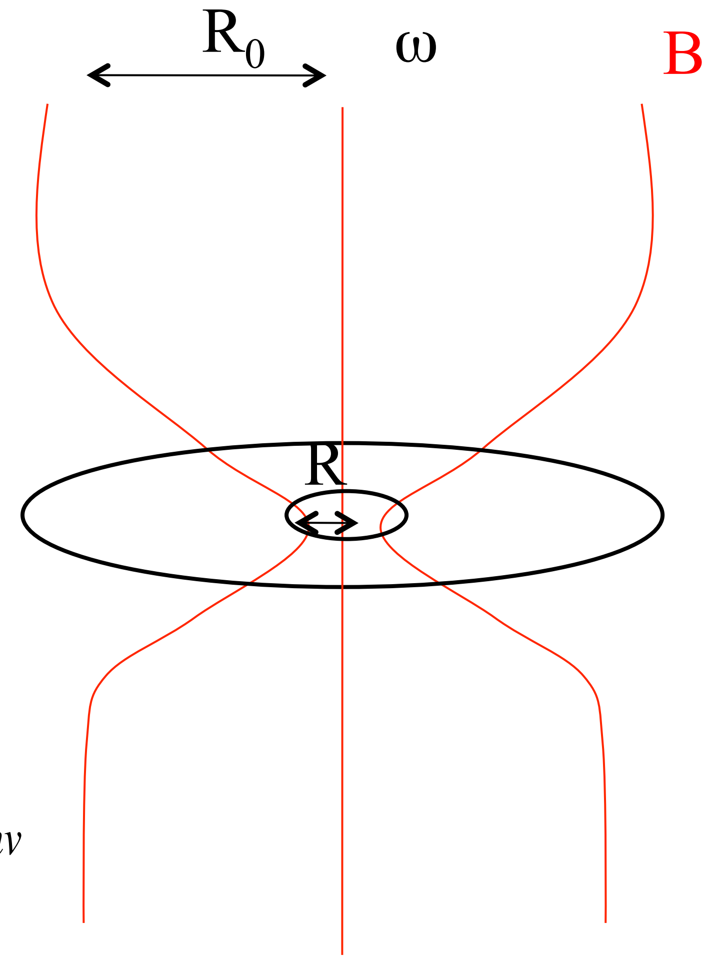
In the aligned configuration, the magnetic braking can be much more efficient if the field lines are fanning out (Mouschovias 1991)

$$M_{core} J_{core} \approx M_{env} J_{env}$$

$$\pi \rho_{core} Z_{core} R_{core}^{\ 4} \omega_{core} \approx \pi \rho_{env} \tau_{para} V_a R_{env}^{\ 4} \omega_{env}$$

$$\Rightarrow \tau_{para} \approx \frac{\rho_{core}}{\rho_{env}} \frac{Z_{core}}{V_a} \frac{R_{core}^{\ 4}}{R_{env}^{\ 4}} \frac{\omega_{core}}{\omega_{env}}$$

$$\approx \frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}} \frac{R_{core}^{\ 2}}{R_{env}^{\ 2}}$$



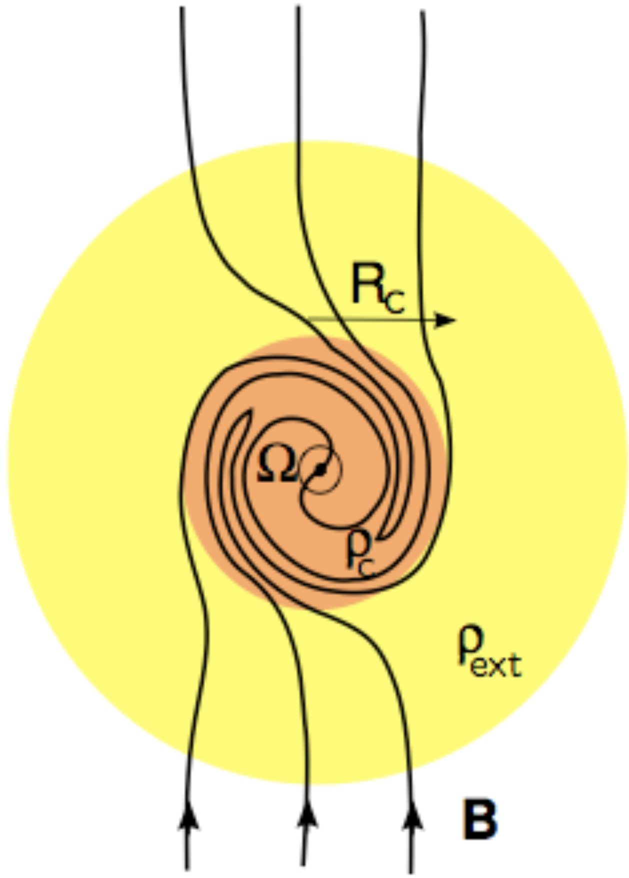
since $M = 2\pi Z_{core} R_{core}^{\ 2} \rho_{core}$ and $\phi = \pi R_{env}^{\ 2} B_{env}$

and assuming corotation $\omega_{core} \approx \omega_{env}$

Thus, the magnetic braking is more efficient when field lines are fanning out

Magnetic braking in the perpendicular case

The geometry of the field lines is complex. It is traditionally assumed that Bα1/R (Mouschovias 1991)



$$\pi\rho_{core} Z_{core} R_{core}{}^4 \approx \pi\rho_{env} Z_{core}\left(R_{perp}{}^4 - R_{core}{}^4\right)$$

$$\Rightarrow \tau_{perp} \approx \int_{R_{core}}^{R_{perp}} \frac{dR}{V_a} = \frac{R_c}{2V_a(R_c)}\left(\sqrt{1+\rho_{core}/\rho_{env}} - 1\right)$$

$$\approx \frac{M}{\phi} \times 2\sqrt{\frac{\pi}{\rho_{core}}}$$

since $M = 2\pi Z_{core} R^2 \rho_{core}$ and $\phi = \pi R^2 B$

Comparison between timescales

(Joos et al. 2012)

$$\frac{\tau_{perp}}{\tau_{para}} \approx \frac{\frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{core}}}}{\frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}} \left(\frac{R_{core}}{R_0}\right)^2} \approx \sqrt{\frac{\rho_{env}}{\rho_{core}}} \times \left(\frac{R_{core}}{R_0}\right)^{-2}$$

When the field lines are aligned:
=> the braking is more efficient in the perpendicular case

$$\frac{\tau_{perp}}{\tau_{para}} \approx \sqrt{\frac{\rho_{env}}{\rho_{core}}}$$

When the field lines are fanning out, assuming $\rho \propto R^{-2}$
=> the braking is more efficient in the aligned case

$$\frac{\tau_{perp}}{\tau_{para}} \approx \sqrt{\frac{\rho_{core}}{\rho_{env}}}$$

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

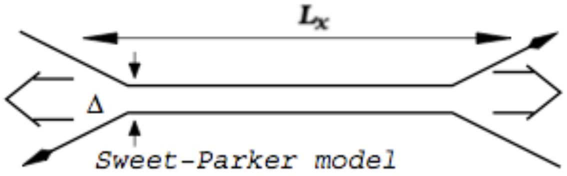
2.3) Influence of B on high mass cores

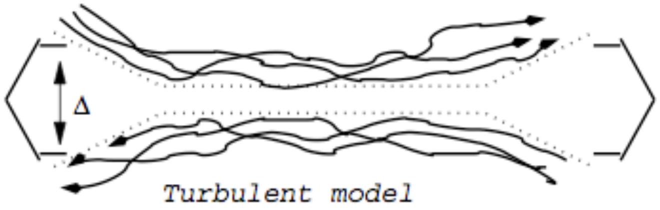
2.4) When magnetic field and radiative feedback collaborate

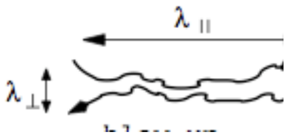
2.5) A crisis: really ?

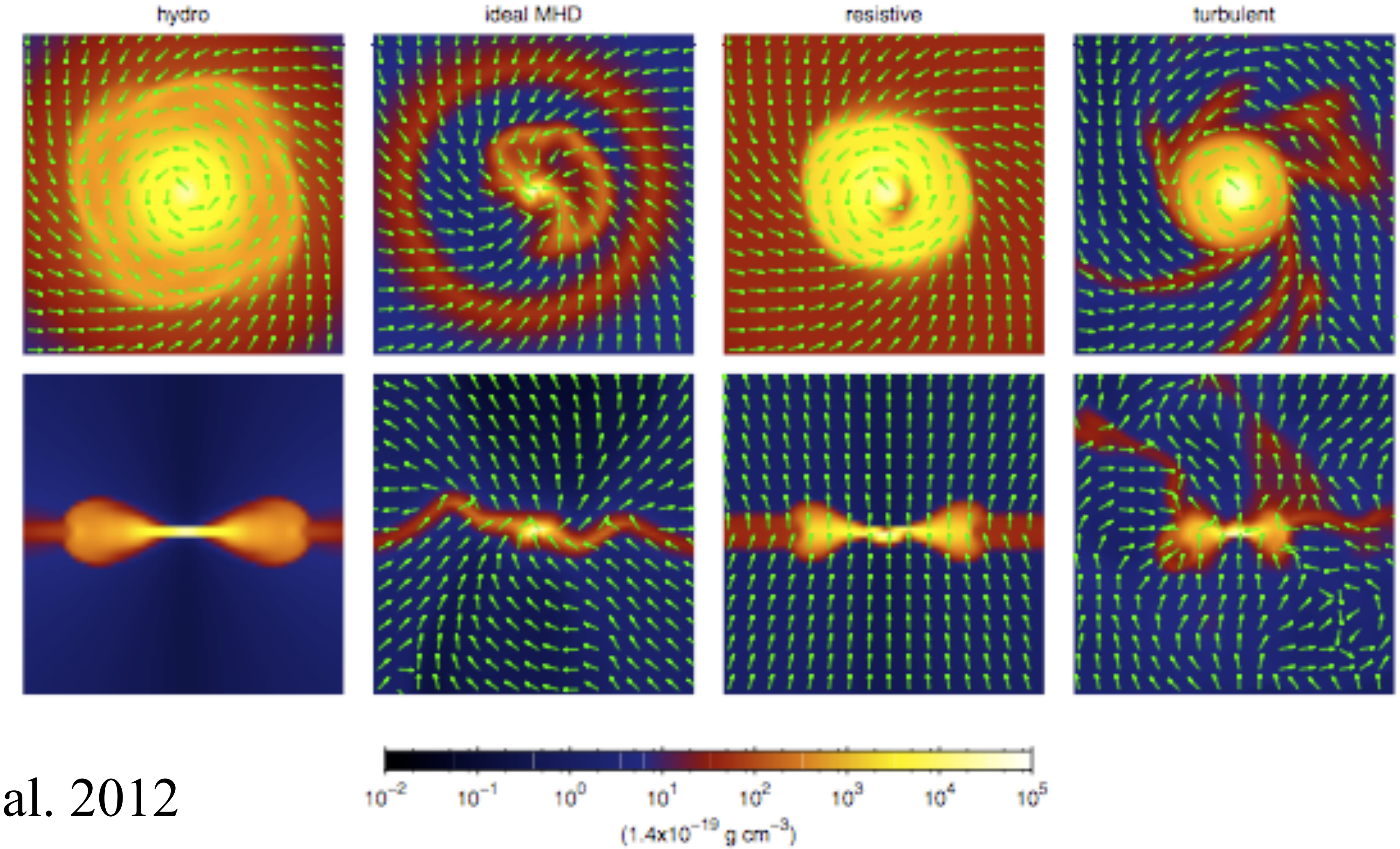
Another limitation:
Impact of turbulence diffusion/reconnection

(Seifried et al. 2011, Santos-Lima et al. 2012)



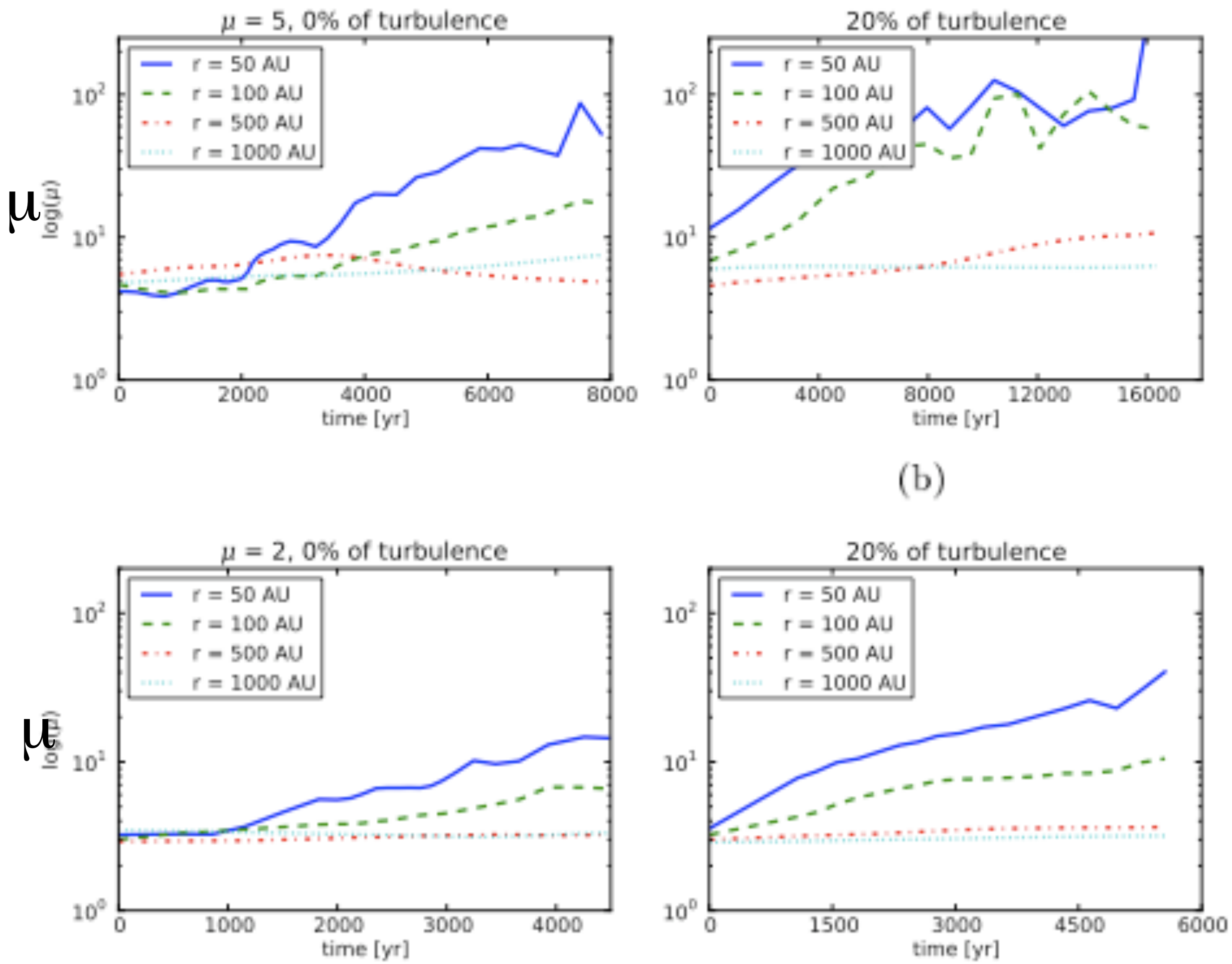






Santos-Lima et al. 2012

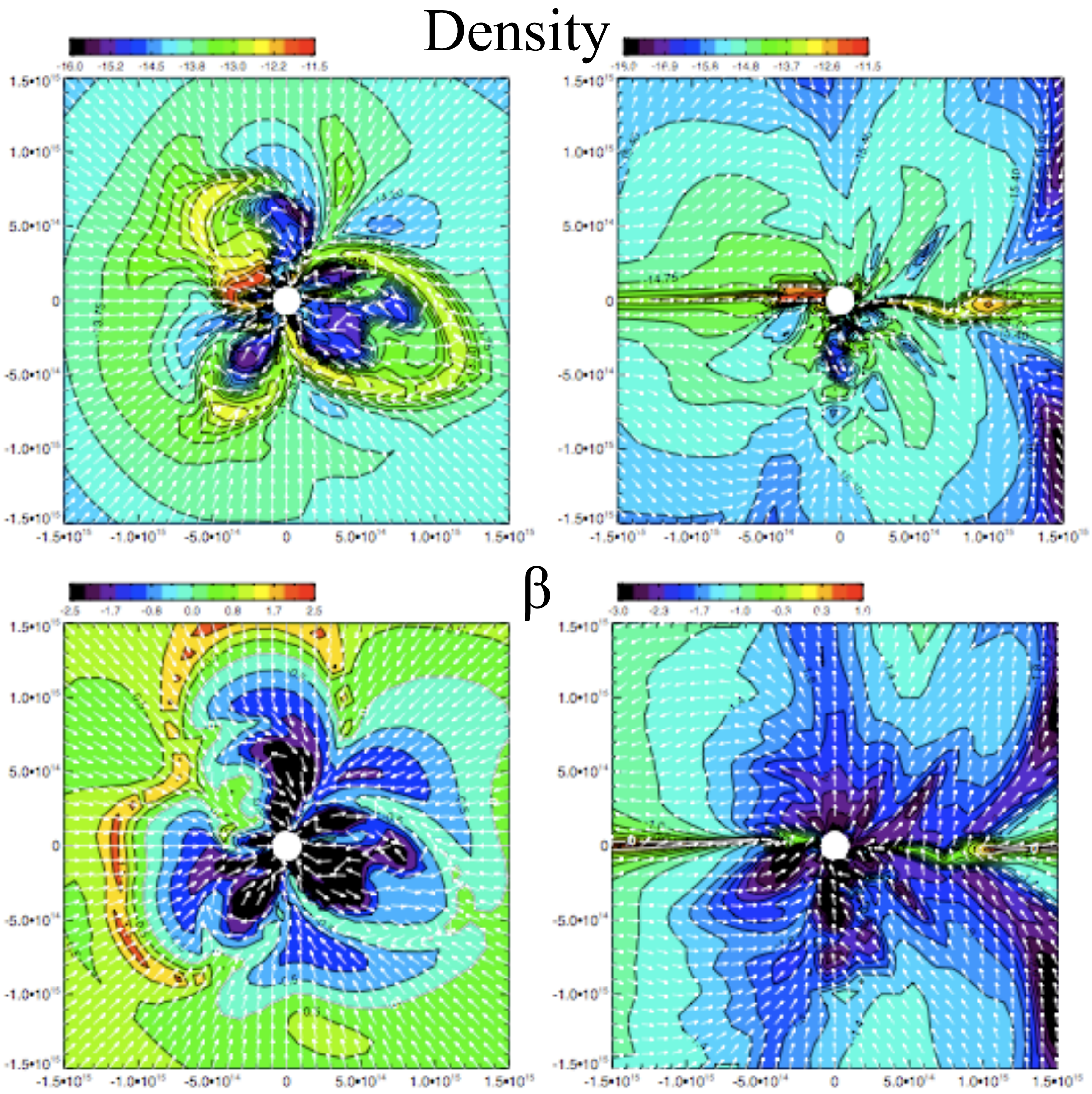
Mass to flux ratio as a function of time for various initial magnetisation and level or turbulence



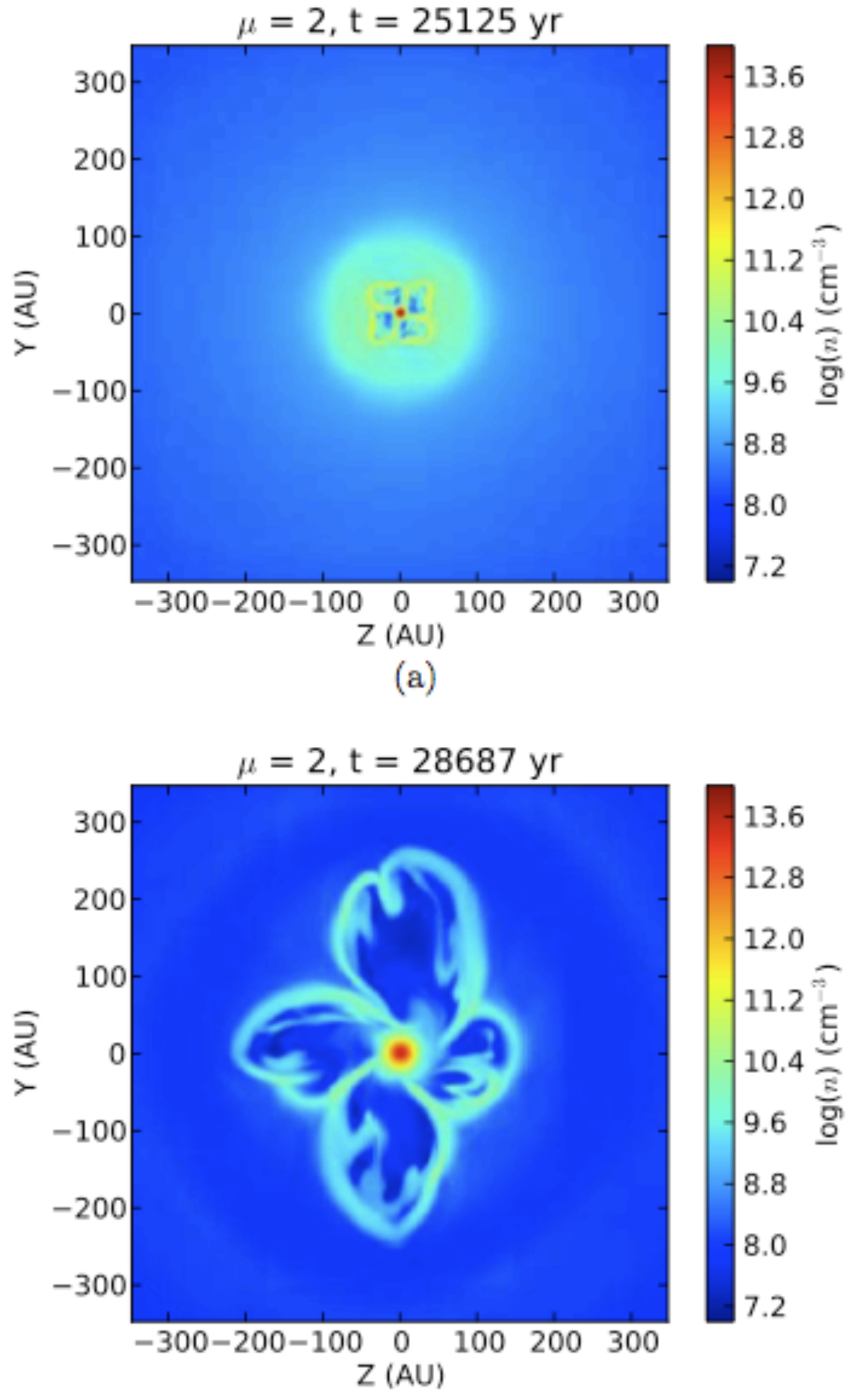
=> Turbulence tends to diffuse the field

Joos et al. 2013

Spontaneous symmetry breaking: the interchange instability



Krasnopolsky et al. 2012



Joos et al. 2012

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

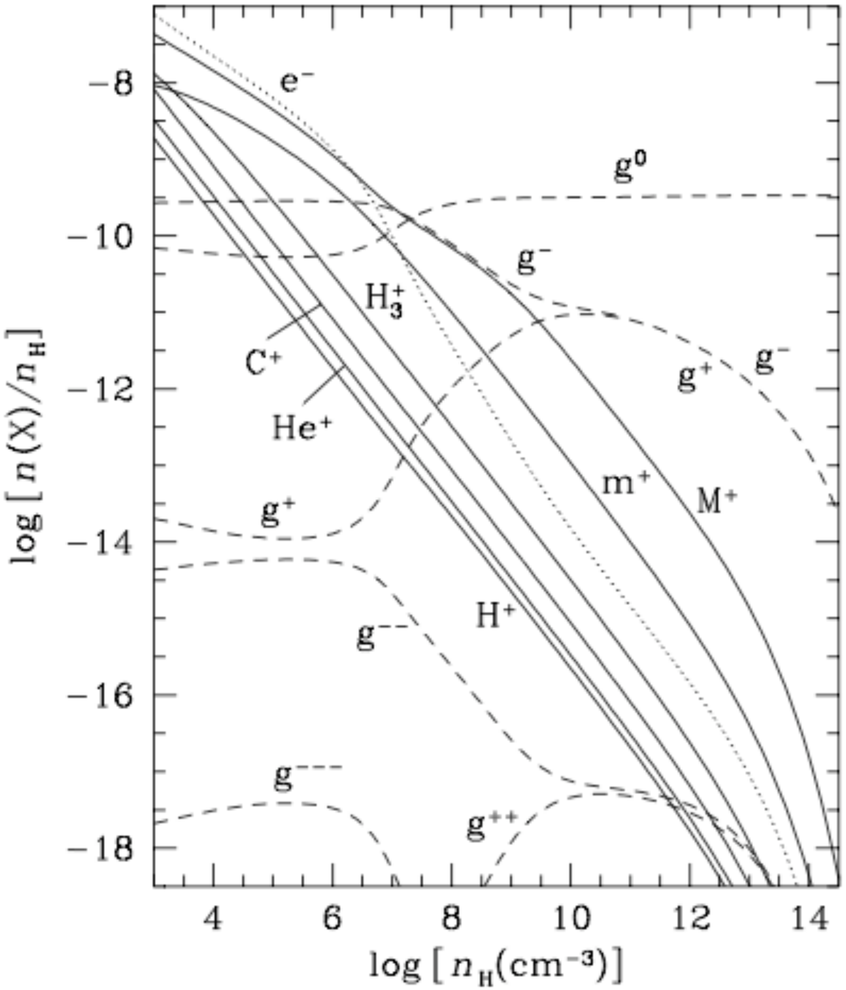
2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

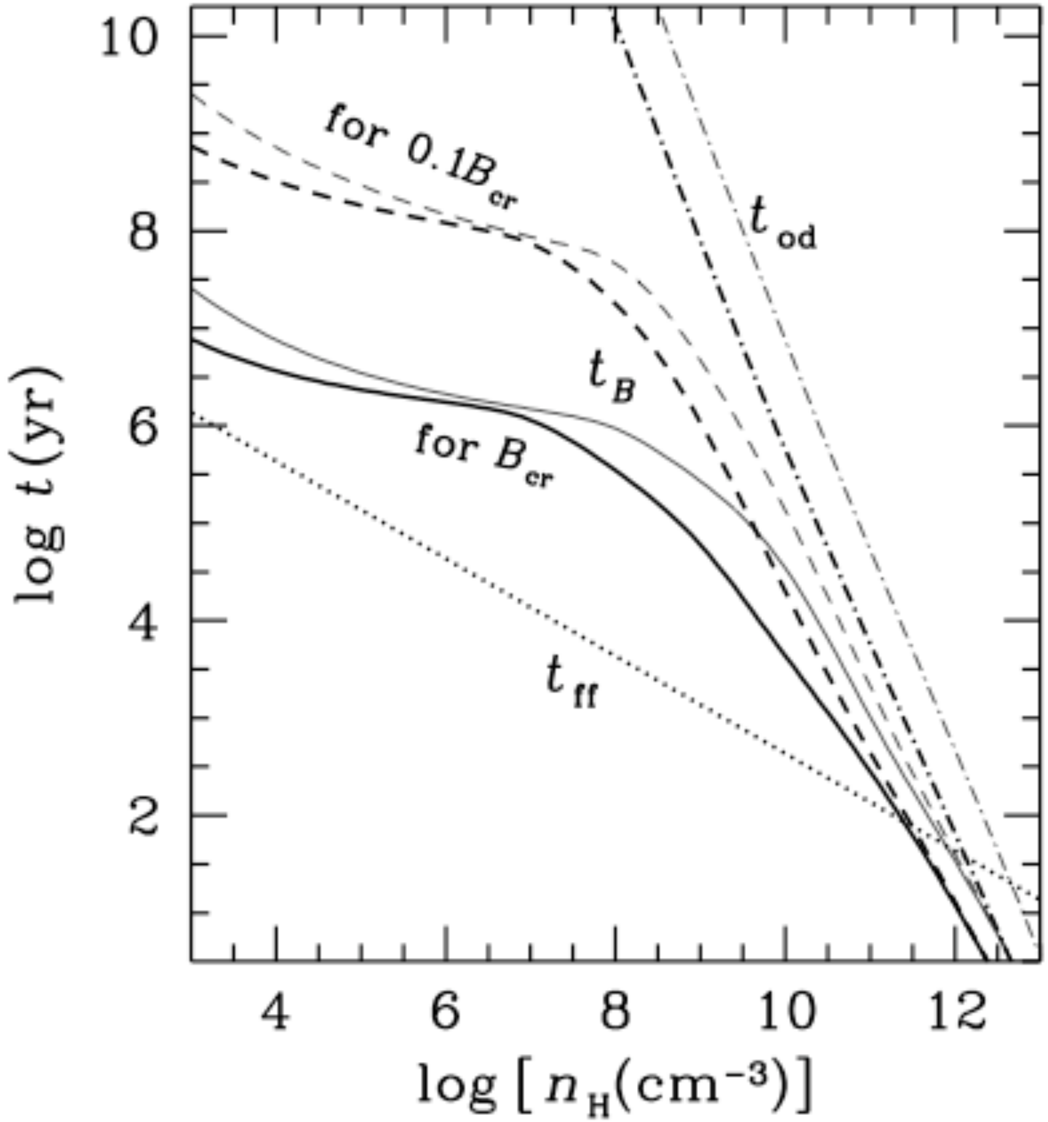
Detailed microphysics implying chemistry network

Abundances of species



Nakano et al. 2002

Diffusion time vs density

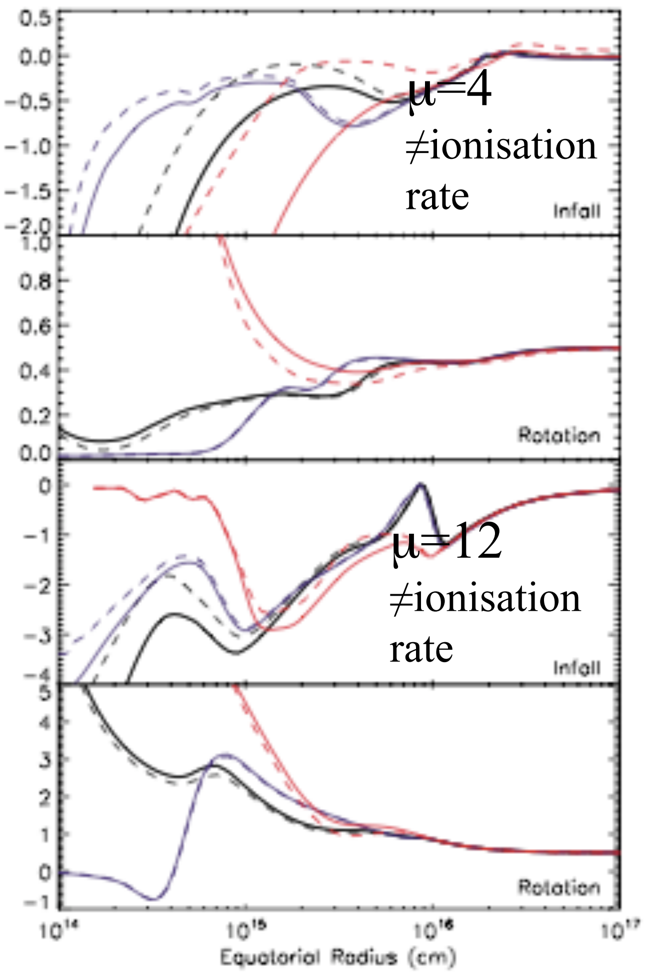


Can ambipolar diffusion modify this?

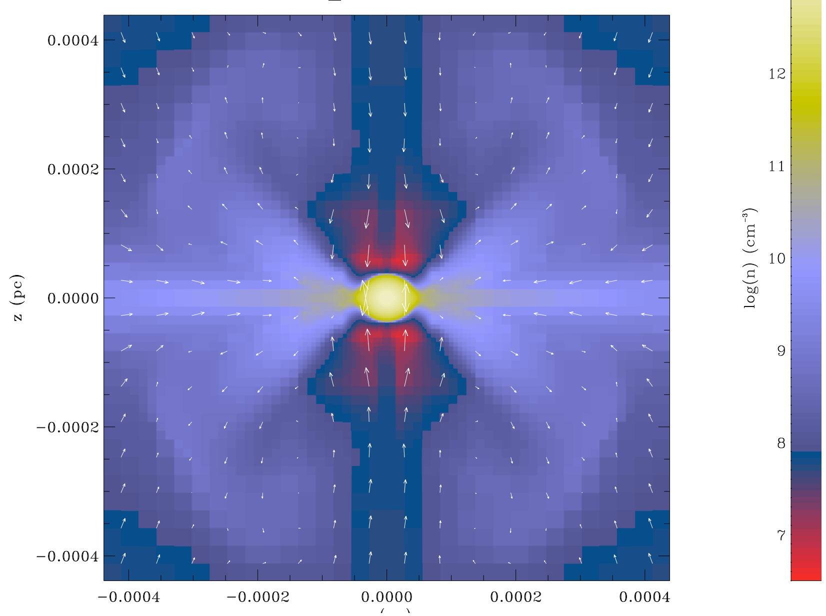
(Mellon & Li 2009, Duffin & Pudritz 2009)

Masson et al. in prep

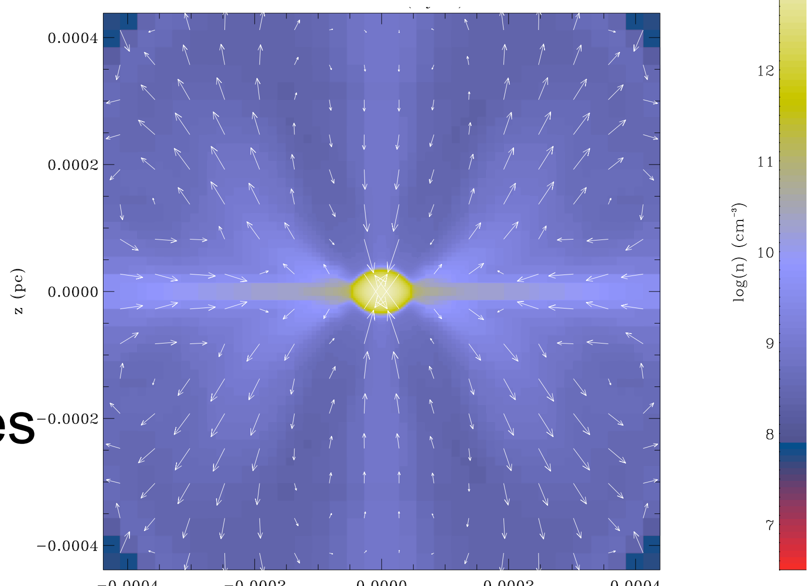
Mellon & Li 09
Collapse with a.d.



With ambipolar diffusion



Without ambipolar diffusion

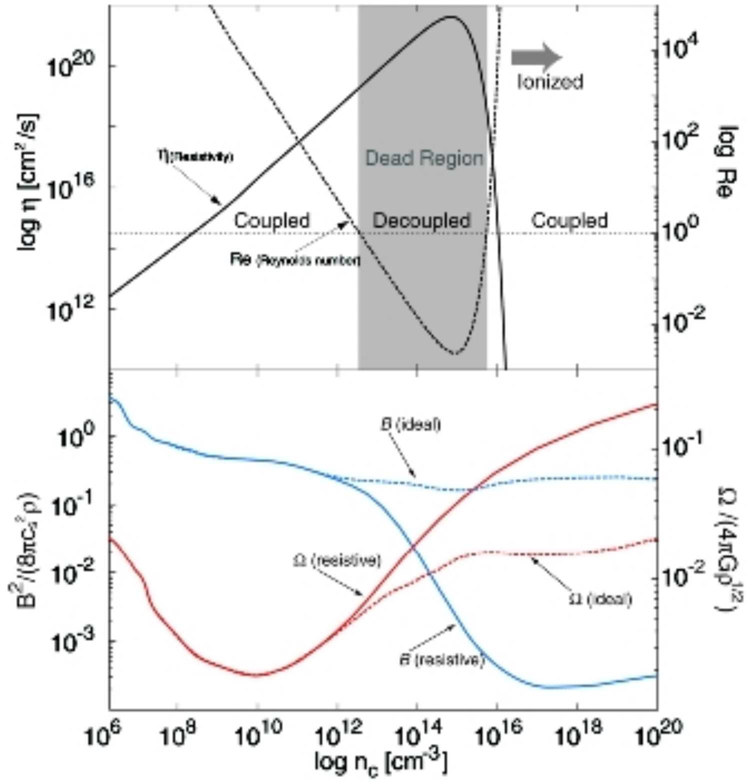


τ_{amb}/τ_{ff} = 8 for critical cores

τ_{amb} α B^2=>slow!

Impact of ohmic dissipation (a solution to the flux problem ?)

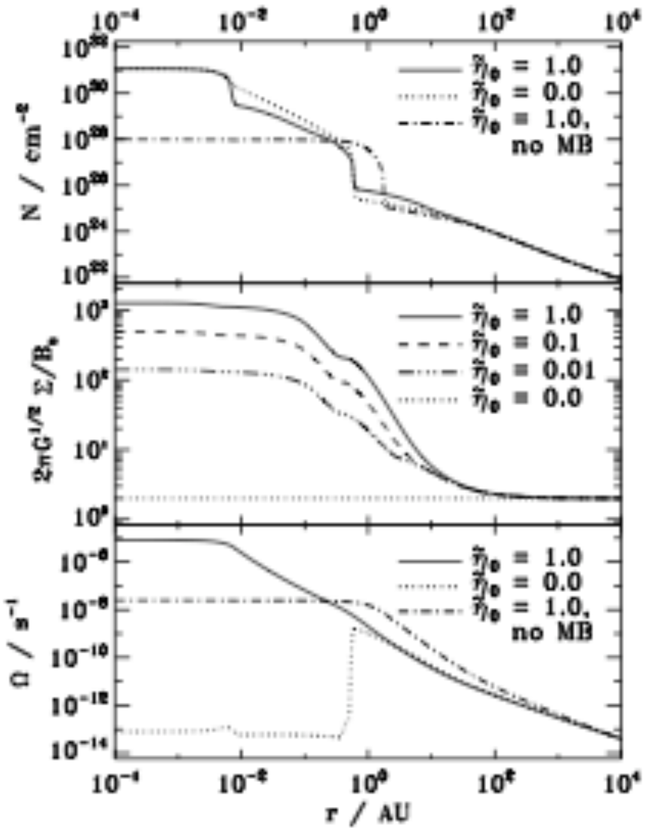
Machida et al. 2007



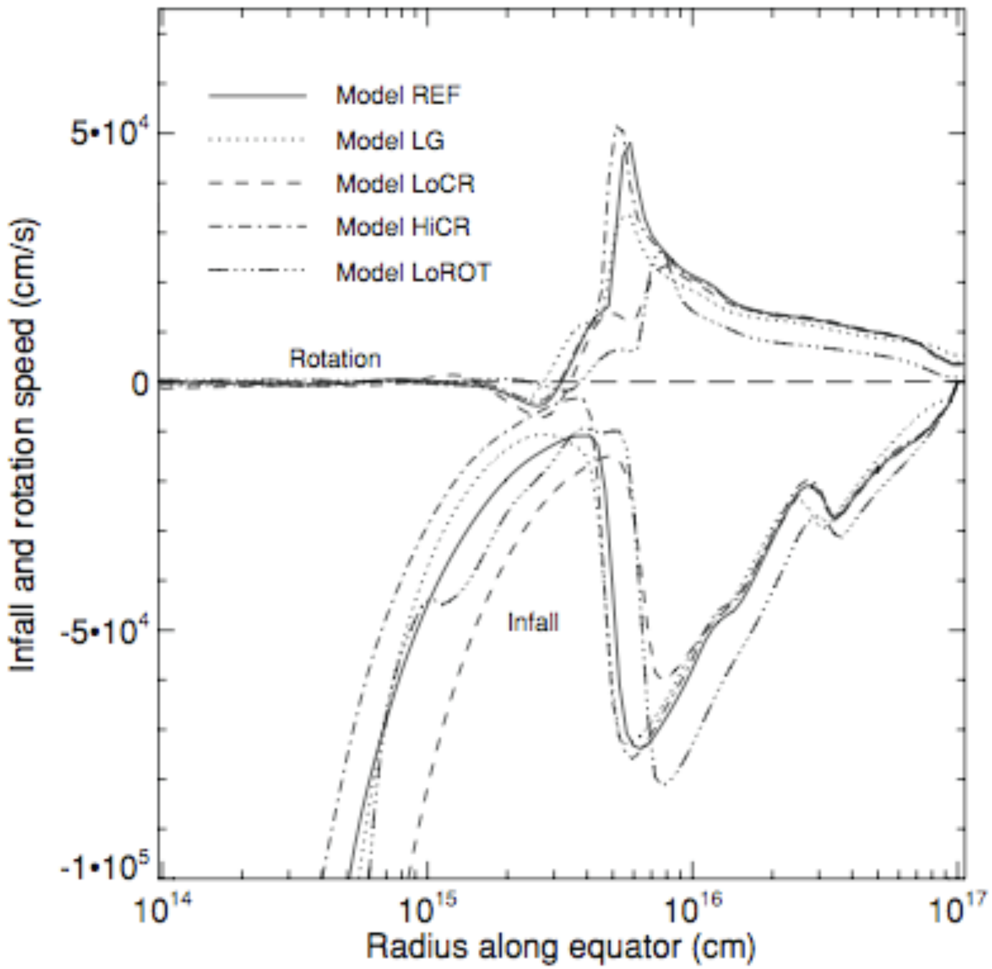
Interestingly: Desh and Mouschovias, Nakano et al. (2002) predicts that a lot of flux should be lost at densities larger than 10^{11} cm^{-3}(grains carry the charge).

First calculation with resistive MHD done by Machida et al. 2007
Characteristic scales of about 10-20 AU
⇒**Formation of compact disks**

Dapp & Basu recent work (1D calculation)



However, Li et al. 2011 performed a series of simulations taking into account ambipolar diffusion, Hall effect and Ohmic dissipation and find no disk at all…



Confused situation

Could be due to:

-Li et al. have a sink whose radius is 6AU

-Machida et al. perform 3D non-axisymmetric runs while Li et al. perform 2D runs. Possibly due to enhanced transport/flux lost in Machida et al. ?

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

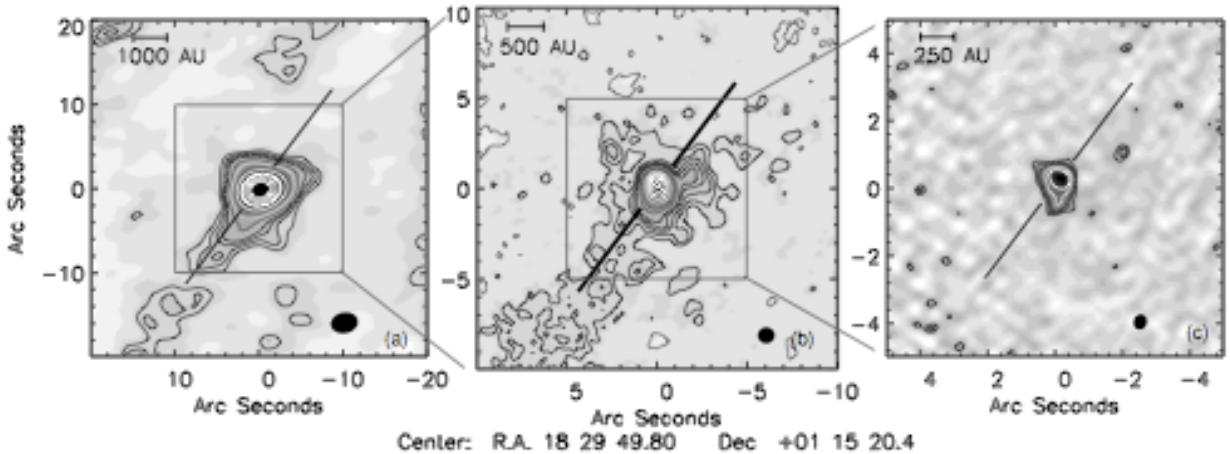
2.5) A crisis: really ?

Are there disks at the class 0 stage ?

Difficult issue because strong emission from the envelope that must be removed.

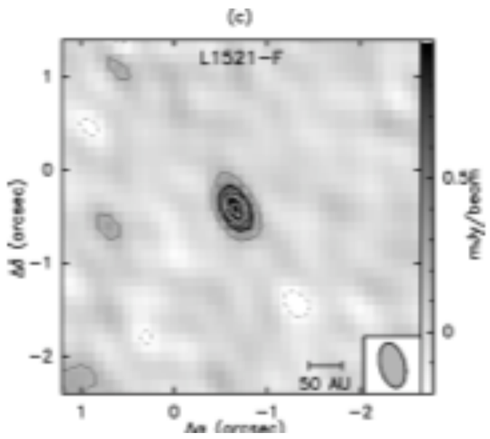
-Jorgensen et al. claim to infer disks from their modeling (disk is not resolved) but Brinch et al. (2009) do not see rotation in some of them

-Enoch et al. (2009) claim to resolve a 1 Ms disk in a 8 Ms source but conclusion depends on assumptions (density profile) for the envelope

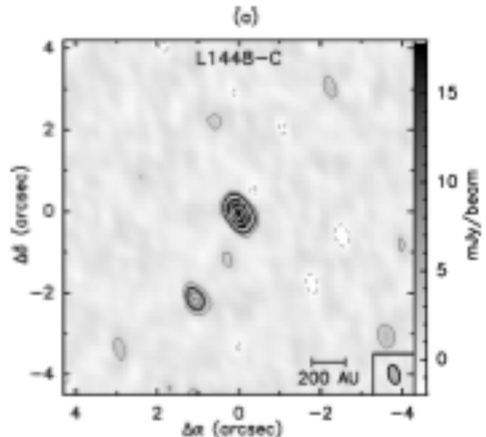


-Maury et al. (2010) do not see disks (5 sources) larger than 50 AU and very little fragmentation at scales smaller than 500 AU

a source in Taurus



a source in Perseus



Comparison of the PdBI maps with MHD simulations

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to Maury et al. 2010 Observations.

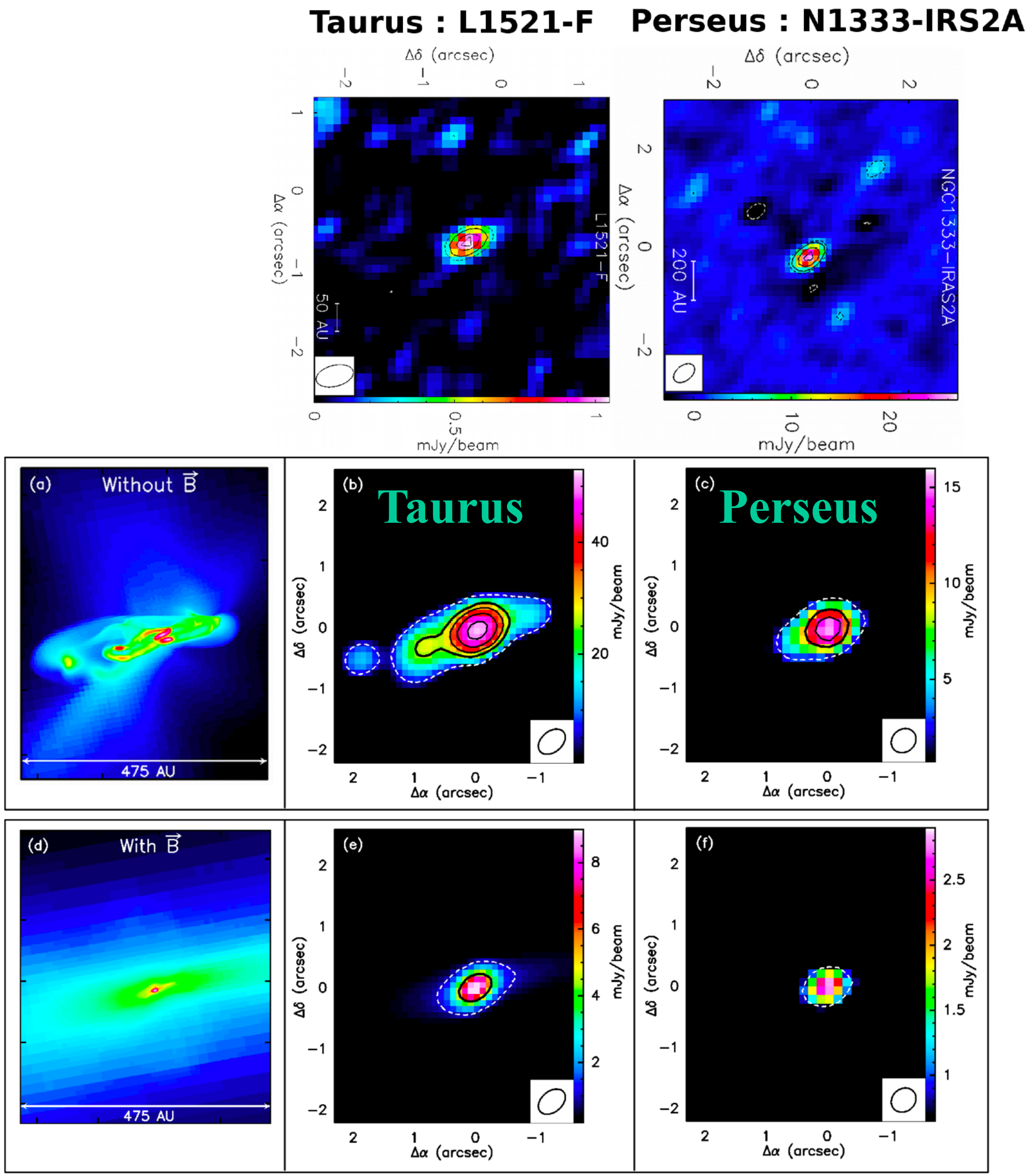
→ MHD simulations ?

MHD simulations : produce PdB-A synthetic images with **typical FWHM ~ 0.2" - 0.6"**

Similar to Class 0 PdB-A sources observed !

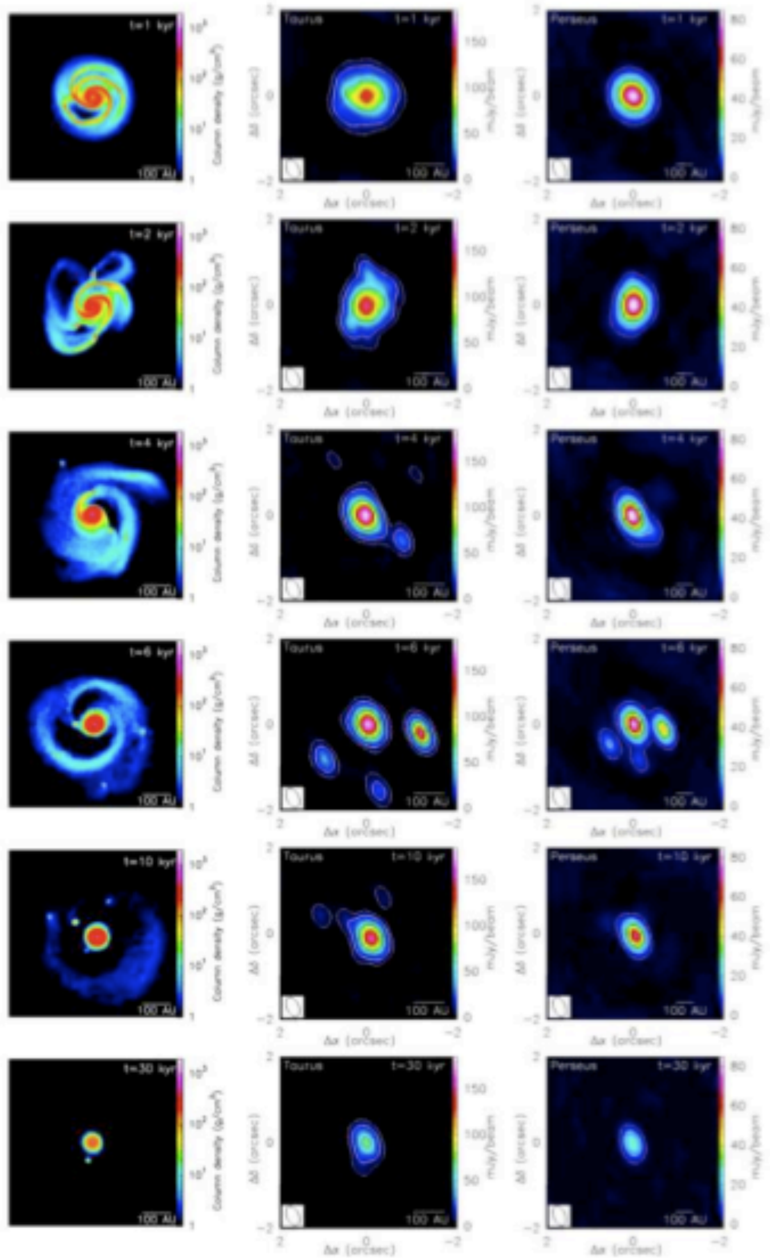
↓

need B to produce compact, single PdB-A sources.



Maury et al. 2010

An alternative view: Stamatellos et al. (2010) propose that massive disks form and quickly fragment. Thus the chance to see them is weak.



Some conclusions regarding disk formation and braking:

-magnetic field modifies very significantly the early disk formation

-for intermediate magnetization, the geometry is important and braking is more efficient in the aligned case

-turbulence is reducing the braking because it diffuses the field and naturally generates non-aligned configuration, it helps forming disks

-non-ideal MHD may help but some debate remains. It seems reasonable that it should help forming small disk

-Unclear that there is a *problem* since very few observations of class 0 disks are available

-We need to get a distribution of inner structure and of initial conditions (field strength and configuration, rotation) before we can conclude whether the problem is understood

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation “crisis” for low mass cores ?

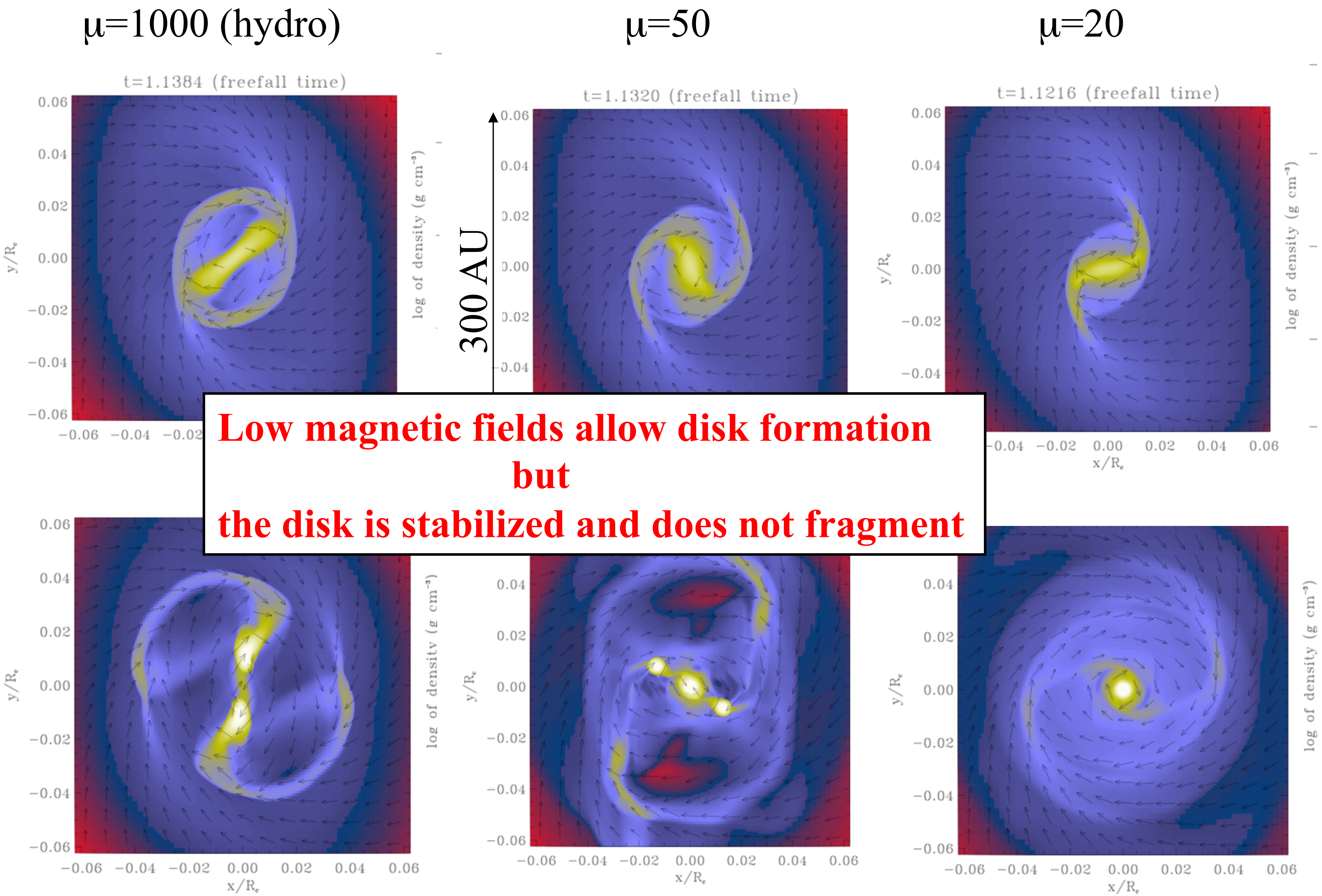
2.2) How to solve it ?

2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

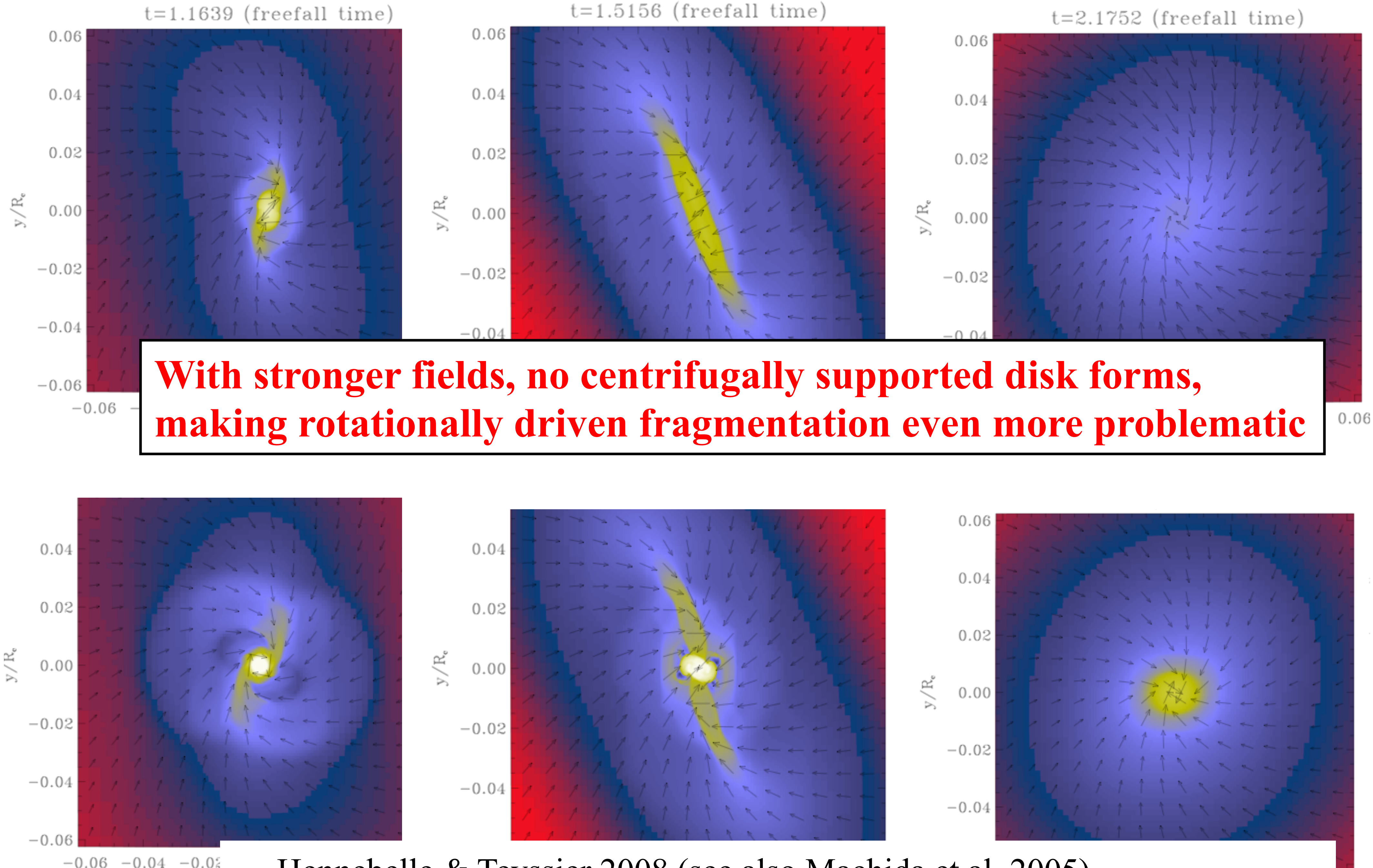
Influence of a weak magnetic field on the fragmentation



Hennebelle & Teyssier 2008 (see also Machida et al. 2005)

For smaller μ, magnetic braking removes the disk

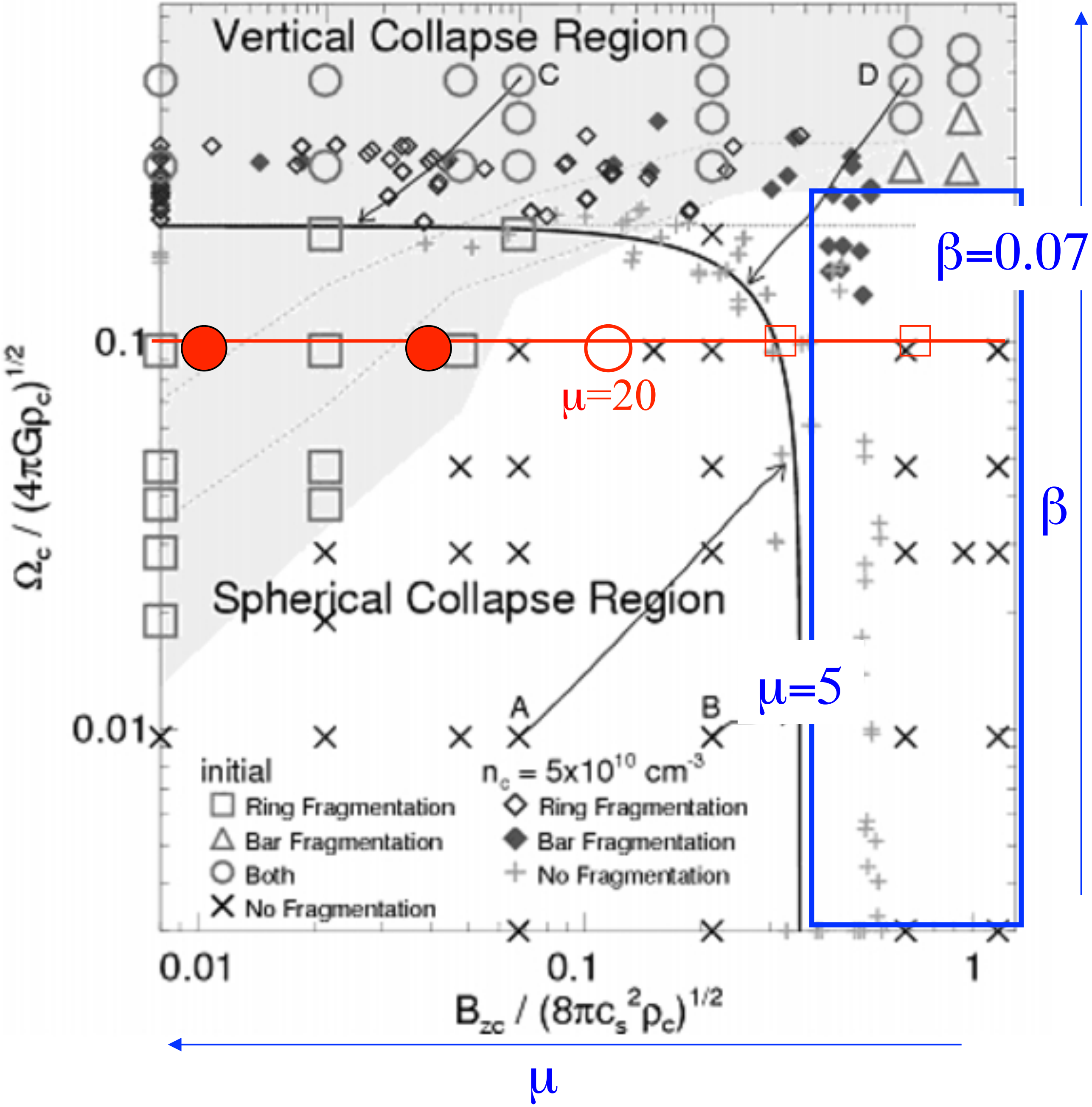
μ=5 μ=2 μ=1.25



With stronger fields, no centrifugally supported disk forms, making rotationally driven fragmentation even more problematic

Hennebelle & Teyssier 2008 (see also Machida et al. 2005)

Fragmentation: results of Machida et al. 2005



Observations
(Crutcher 2004,
Goodman et al. 1993,
Caselli et al. 2002)

μ<5 (may be <2)
β<0.07
(β=0.02, typical)

Hennebelle & Teyssier 2008
amplitude of perturbation: 0.1
μ: 1000-1.25
corrected β about 0.01
(uncorrected β =0.045)

- □ No class-0 disk
- ○ Class-0 disk no fragmentation
- ● Fragmentation

$$\Omega_c / (4\pi G \rho_c)^{1/2} = \sqrt{\beta}, \quad \beta = E_{rot} / E_{grav}$$

$$B_{zc} / (8\pi C_S{}^2 \rho_c) \approx \sqrt{3} / (\sqrt{\alpha}\mu), \quad \alpha = E_{therm} / E_{grav}, \mu = (M/\phi)/(M/\phi)_{crit}$$

Why magnetic field stabilizes the disk so efficiently ?

Consider a uniformly rotating, self-gravitating, magnetized layer. Lynden-Bell (1966) obtained the dispersion relation:

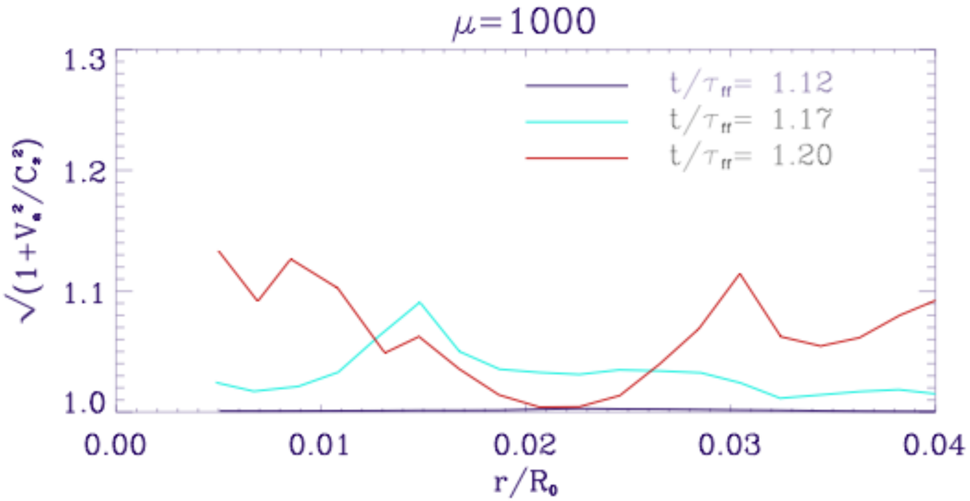
$$\omega^4 - \left[4\Omega^2 - 2\pi G \Sigma_0 |k| + k^2 \left(c^2 + \frac{B^2}{4\pi\rho} \right) \right] \omega^2 + \frac{(k^2 c^2 - 2\pi G \Sigma_0 |k|)(\mathbf{k}.\mathbf{B})^2}{4\pi\rho} = 0 \qquad (1)$$

It entails a modified sound speed due to the magnetic pressure forces => stabilizing effect.

But destabilizing contribution of the magnetic tension
⇒Configuration unstable

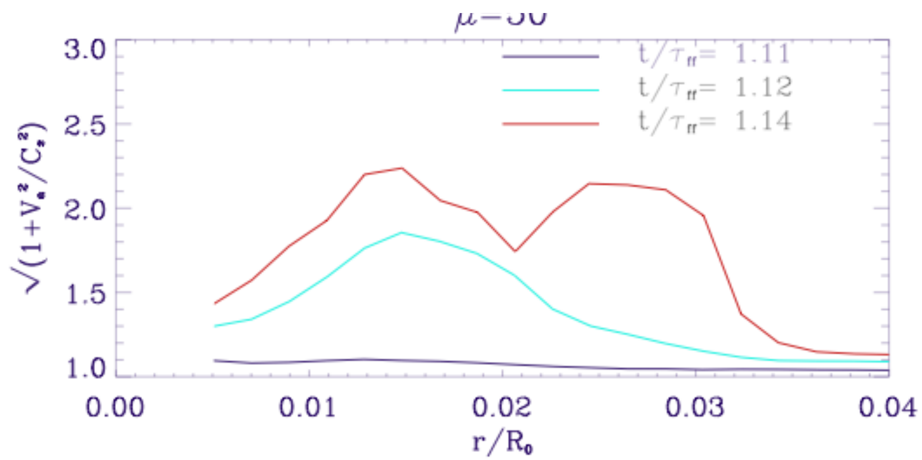
However, in a differentially rotating system (like a disk in Keplerian rotation), a toroidal magnetic field is quickly generated and the first effect becomes dominant.
(Elmegreen 1987, Gammie 1996)

Growth of the toroidal magnetic field within the disk

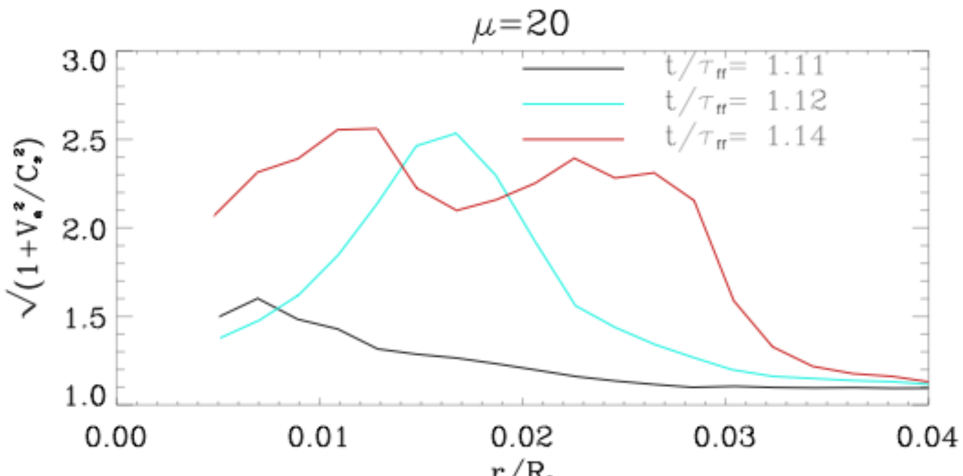


Importance of V_a/C_s

for various μ and various times



=>Compatible with the assumption that the toroidal field, stabilizes the disk.



1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

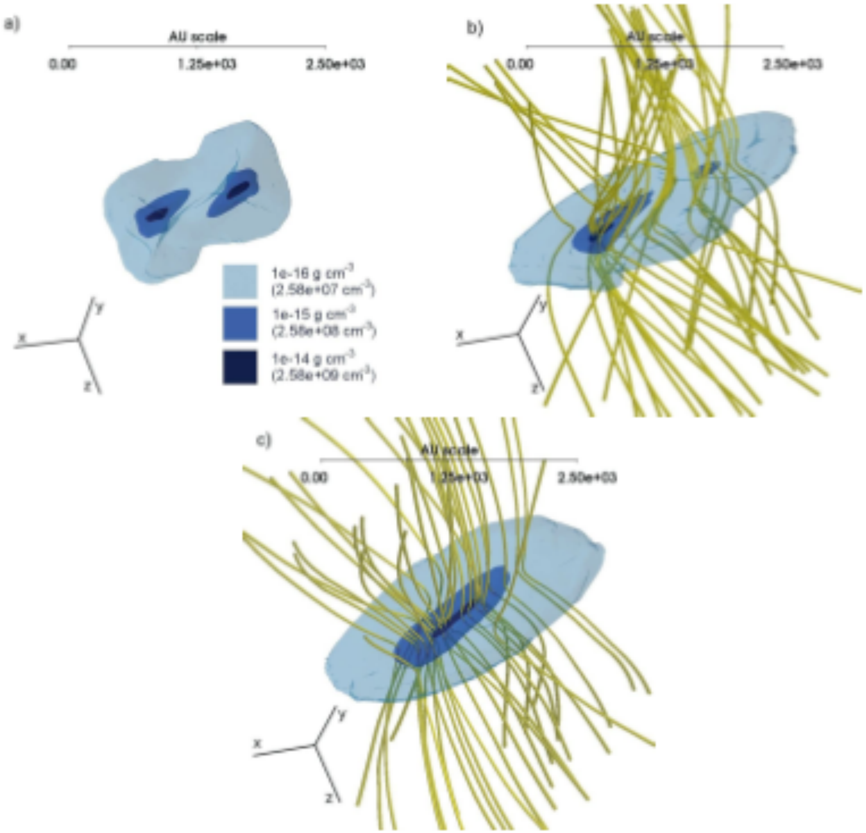
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

Influence of non-ideal MHD ?

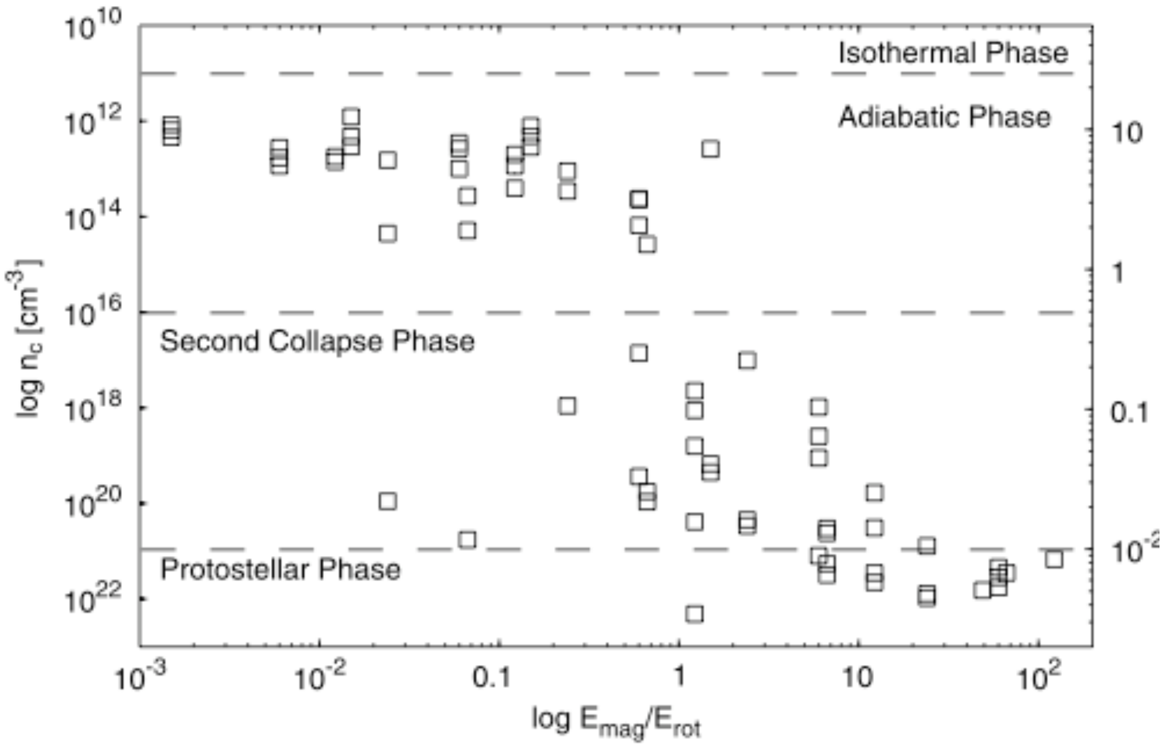
Ambipolar diffusion

Duffin & Pudritz 09
A fastly rotating model



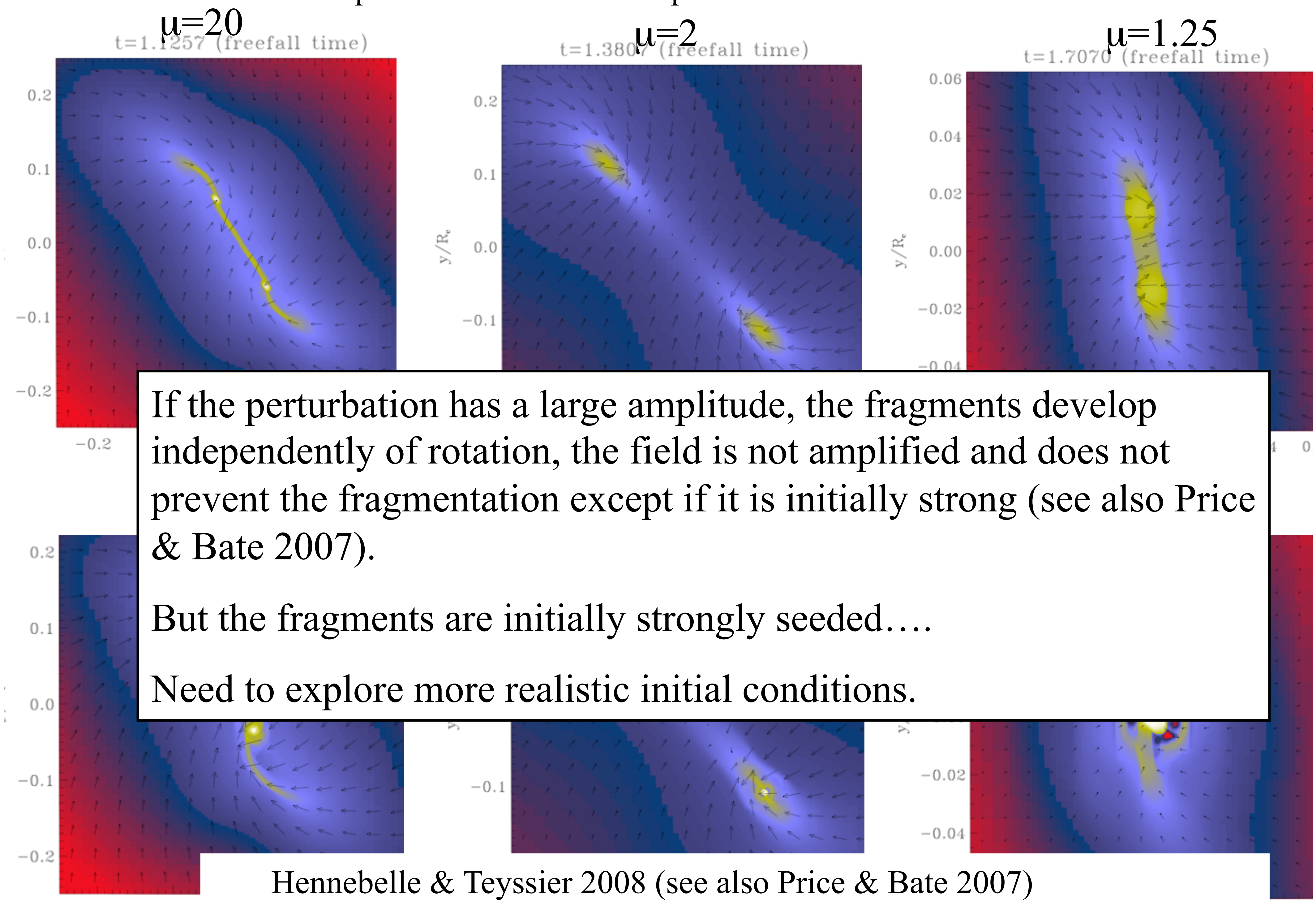
Ohmic dissipation

Machida + 08
147 simulations treating 2nd collapse
102 simulations fragment
Simulations with realistic initial conditions fragment only during the second collapse



Effets of initial density perturbations ?

m=2 perturbation with an amplitude of 50%



If the perturbation has a large amplitude, the fragments develop independently of rotation, the field is not amplified and does not prevent the fragmentation except if it is initially strong (see also Price & Bate 2007).

But the fragments are initially strongly seeded….

Need to explore more realistic initial conditions.

Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation “crisis” for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

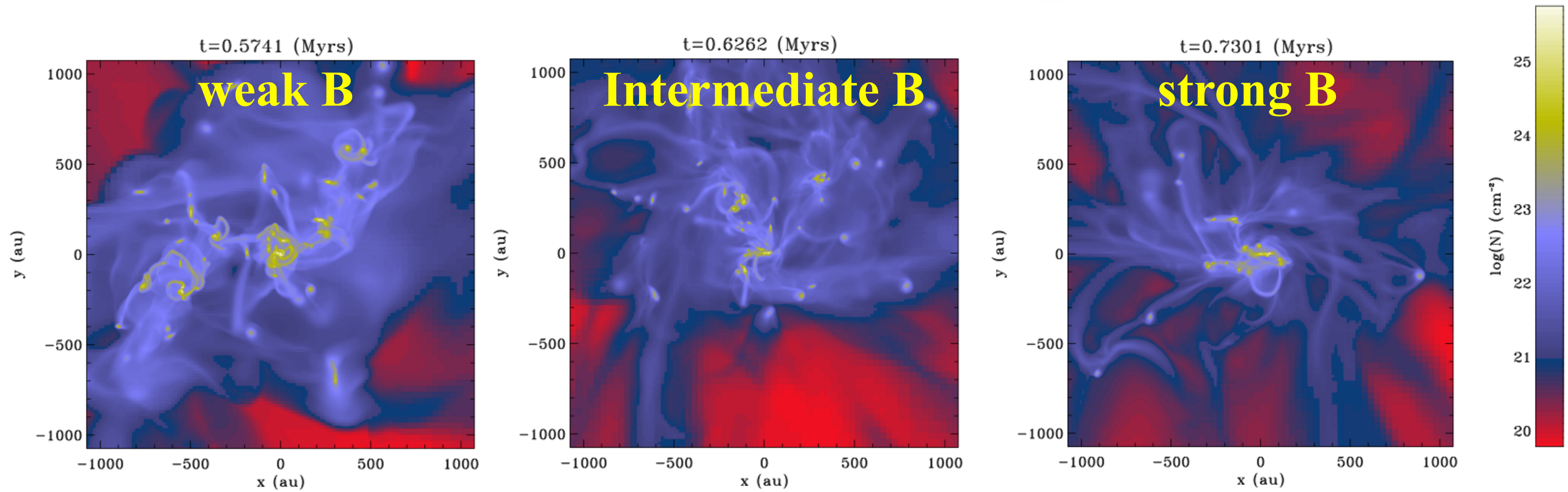
2.5) A crisis: really ?

100 M$_\odot$ magnetized, turbulent and dense barotropic core

(other related works : Peters et al. 2010, Seifried et al. 2012)

Turbulence is initially seeded. Eturb/Egrav ~20%

In the case of a massive turbulent core, magnetic field reduces, though, do not suppress fragmentation



μ=120 μ=5 μ=2

Hennebelle et al. 2011

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation “crisis” for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

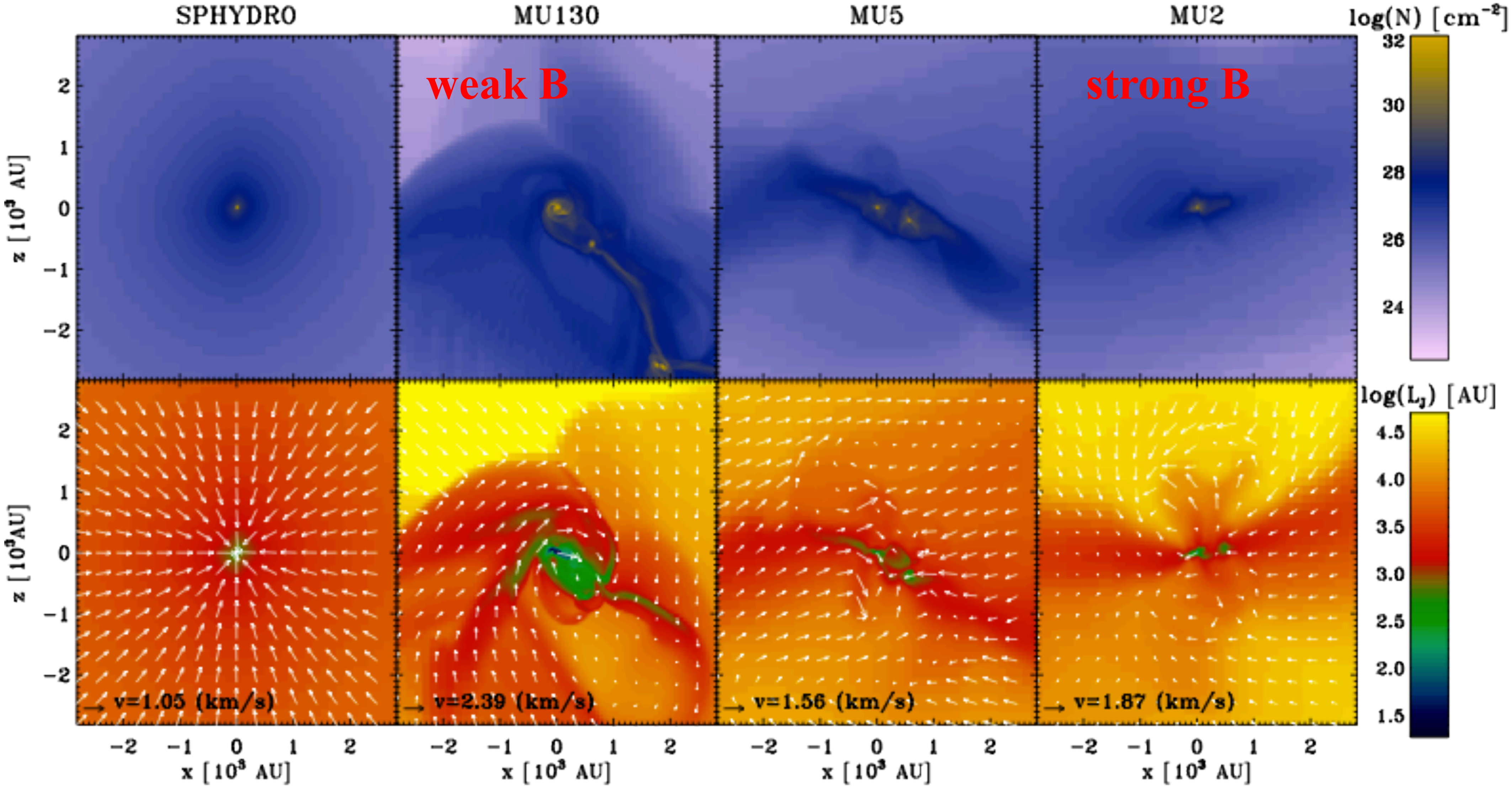
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

100 M$_\odot$ turbulent dense core collapse

Radiation taken into account using grey approximation and diffusion approximation

Eturb/Egrav=20% initially

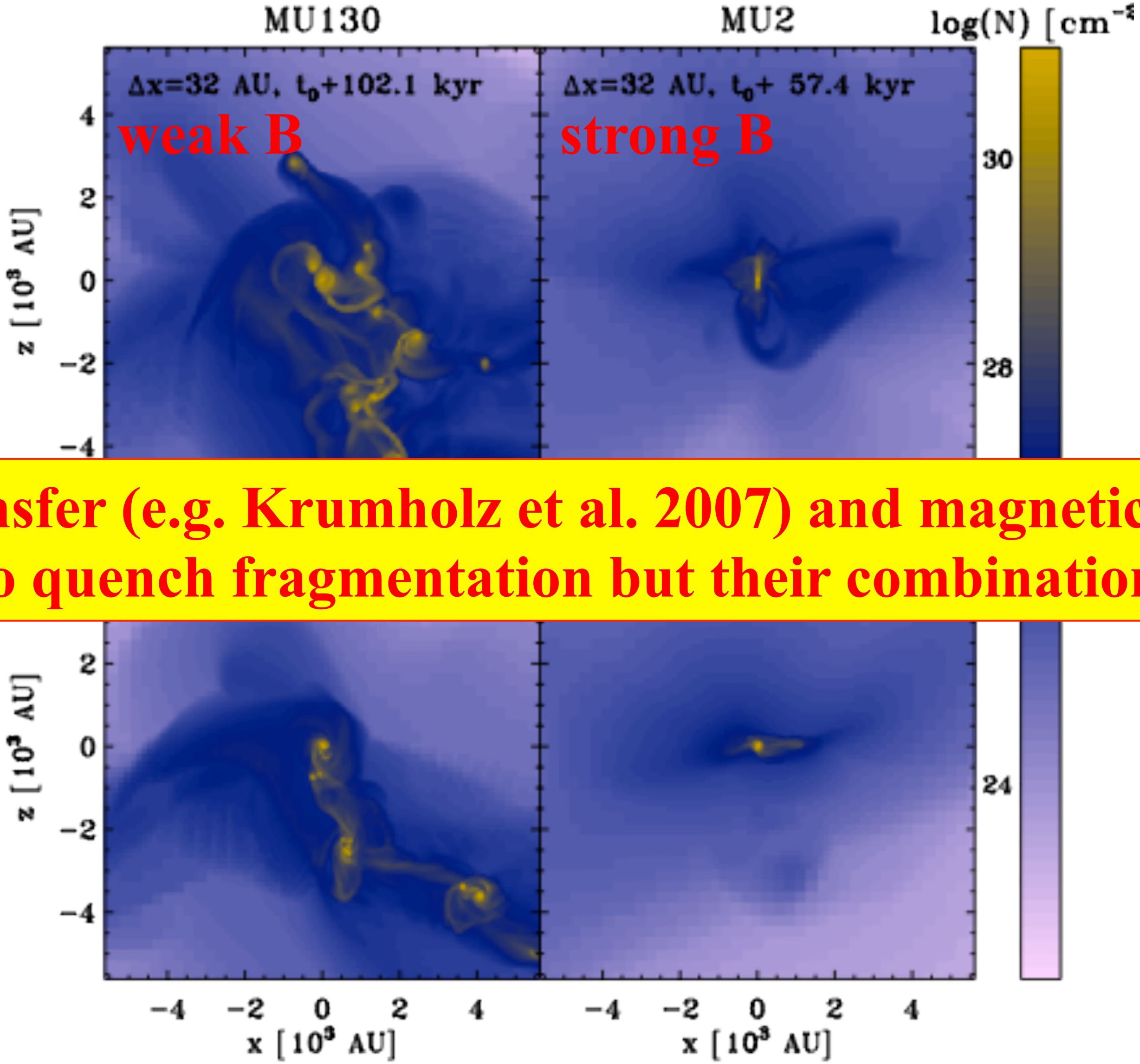


Commerçon, Hennebelle & Henning, ApJL 2011

(see also Myers et al. 2013)

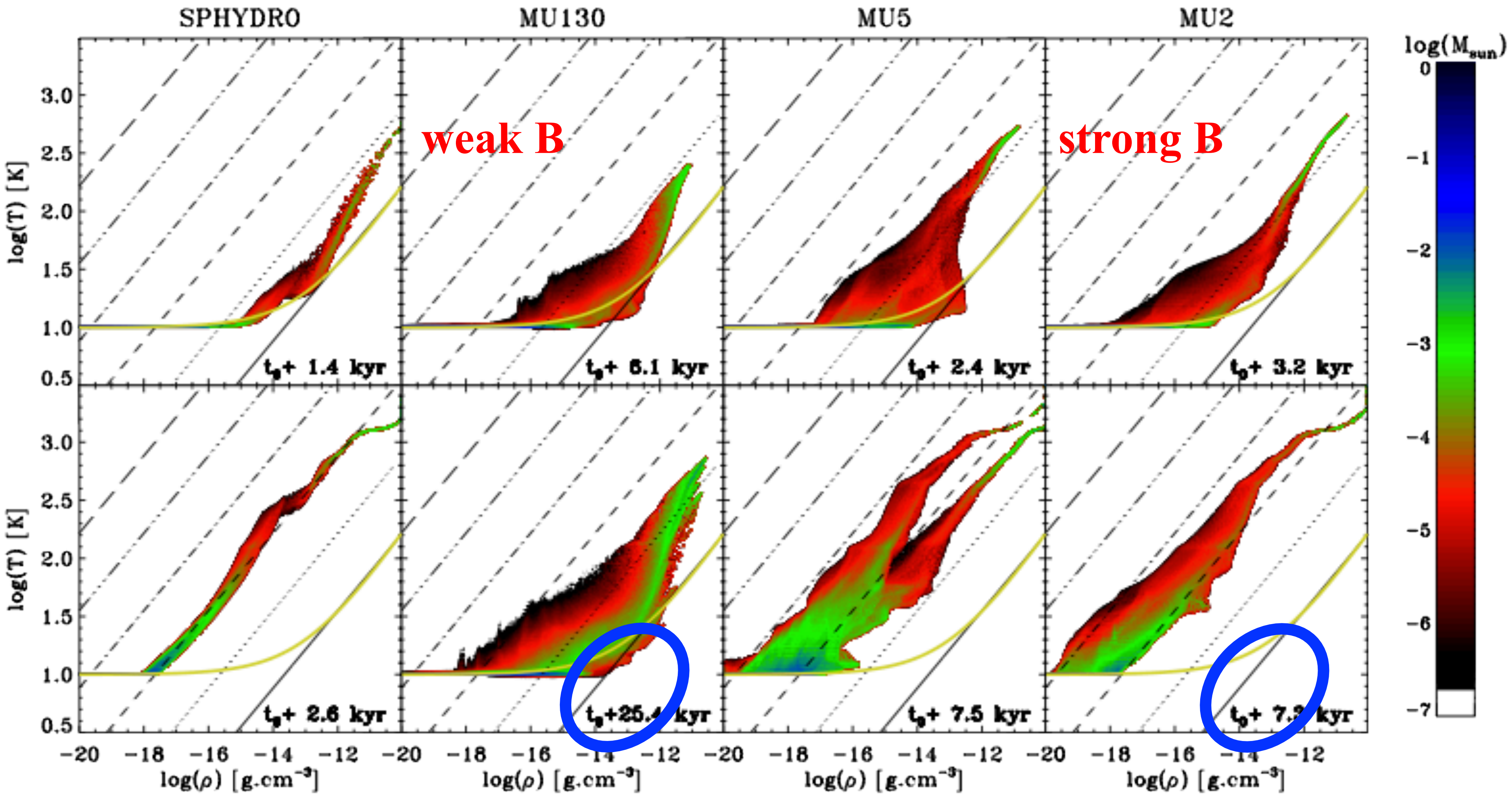
100 M$_\odot$ turbulent dense core collapse

Trend confirmed with lower resolution runs:



Radiative transfer (e.g. Krumholz et al. 2007) and magnetic field may not be sufficient to quench fragmentation but their combination may be !

100 M☉ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation “crisis” for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

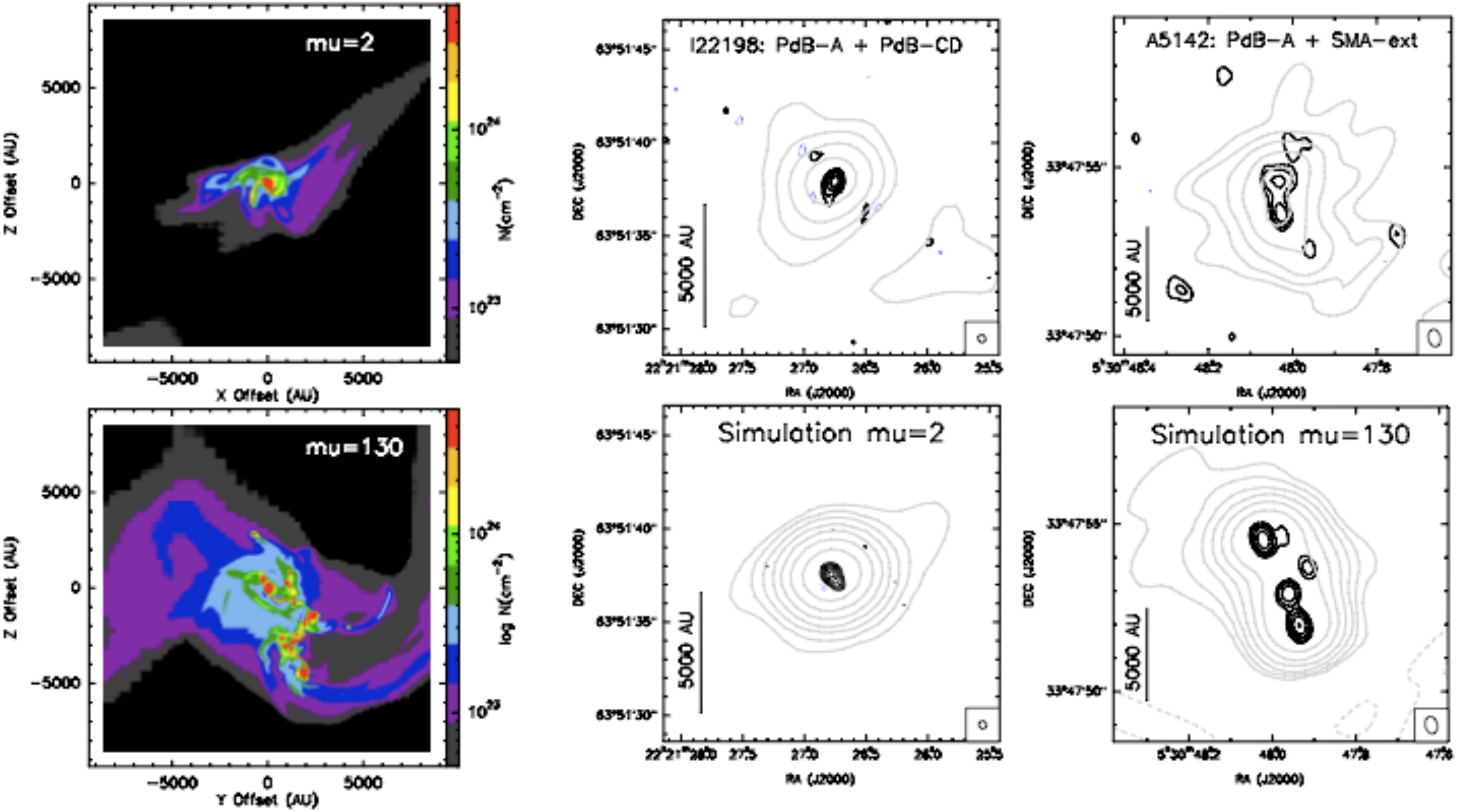
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

Confrontation with real observations of massive class-0 cores

Palau et al. 2013

Some cores show sign of fragmentation some not. No obvious correlation with any observed parameters (mass, rotation…). Magnetic field ?



Conclusions regarding fragmentation

In low mass cores, the magnetic field has a huge impact on the fragmentation, especially “rotationally driven fragmentation”

-”large scale fragmentation” induced by initial large scale density perturbations is possible

-”small scale fragmentation” during second collapse is possible even when the field is strong

In high mass core, the magnetic field reduces but do not suppress fragmentation because the magnetic field is diffused out

The combination of magnetic field and radiative feedback leads to a very significant quenching of fragmentation. Route to form massive stars ?